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CENTRAL BANK DIGITAL CURRENCIES AND THE FUTURE OF MONEY

A NEW THEORETICAL FRAMEWORK, COMPARATIVE INSIGHTS FROM
GLOBAL CASE STUDIES, AND THE ROLE OF ASSET TOKENISATION

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DECLARATION

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ABSTRACT

This research presents a comprehensive analysis of Central Bank Digital Currencies (CBDCs), their potential benefits, challenges, and implications for financial systems. The research is structured across three interconnected papers. The first paper establishes a theoretical contribution by developing a comprehensive framework, designed to assess CBDCs. This research advances novel approaches to model the complexity of CBDCs, by introducing a framework to systematically evaluate and compare distinctive CBDCs' implementations. The research provides insights into effective policies for contemporary economic challenges and offers recommendations for policymakers and national authorities considering CBDCs' implementation. The framework developed in the first paper is applied in the second paper, for comparing three CBDCs, the Sand Dollar launched by the Central Bank of Bahamas, the eNaira established by the Central Bank of Nigeria and the e-CNY developed by the People's Bank of China. The second paper deliver objective assessments of the CBDCs' implementation, analysing the policy and design choices, the technological and governance frameworks, the socio-economic integration strategies, and the sustainability approaches. The comparative study of the three CBDCs reveals valuable information about their national strategies and implementation priorities. The third paper investigates the potential integration of CBDCs with asset tokenisation methods for financial instruments. The study delivers a theoretical contribution by examining how asset tokenisation functions and may integrate with CBDCs for settlement purposes, studying the strengths and weaknesses of this novel approach. This research studies how CBDCs can represent an efficient instrument for settling tokenised digital assets, and it reveals the implications of asset tokenisation within the financial sector, along with its future development potential. Collectively, the research addresses theoretical and analytical foundations in the first paper; it provides comparative insights on global CBDCs' case studies in the second paper, and a future-looking perspective on the interplay between CBDCs and the nascent asset tokenisation field in the third paper, offering lessons learned for central banks, policymakers and consumers, and a forward-looking perspective on the future of money.

KEYWORDS

Central bank digital currency, CBDC, financial inclusion, monetary policy, regulatory oversight, interoperability, programmability, privacy, financial stability, sustainability, asset tokenisation.

CHAPTER 1. INTRODUCTION

Central Bank Digital Currencies (CBDCs) embody a new payment system that central banks can implement and digitally operate under their authority. CBDCs represent the third form of base money, along with cash in circulation and bank reserves. This technology has the potential to transform the entire process of money creation, transfer and usage, leading to improved payment systems, enhanced monetary policy and broader financial access. CBDCs may introduce new privacy risks and cybersecurity threats, they may affect financial stability and the evolving balance of responsibilities between central banks and commercial banks. The author presents an interconnected series of three papers to research this topic, with the aim to provide an in-depth and systematic study on CBDCs. This series investigates various aspects of CBDCs which encompass their theory, practical application processes, along with upcoming development prospects. Each paper builds upon the previous one, providing readers with a comprehensive framework, a detailed and methodical understanding of CBDCs and their design choices, their implications for financial systems, and the opportunities for development and future research.

The first paper, included in Chapter 2, has the primary goal of delivering a comprehensive framework for the analysis, assessment, and comparison of CBDC implementations. The research questions addressed in this paper include how a structured framework could be developed to analyse and compare CBDCs' implementations, what are the key design and technical features of CBDCs and what are the strengths and weaknesses of different CBDC models. The research investigates the essential elements for achieving a comprehensive understanding of CBDCs, including their design principles and technical features. The paper investigates the unique options that are available for multiple applications of CBDCs. The research develops a comprehensive framework that combines four dimensions into one cohesive structure. The research methodology employs a critical literature review, combining findings to create a new theoretical framework for the in-depth analysis of CBDCs, systematically identifying relevant studies, evaluating them to assess current knowledge and future research areas, across four main areas, to conduct a thorough assessment of the policy, regulatory and governance structure, the design and technology requirements, along with the socio-economic and financial integration factors and the sustainability and inclusivity aspects. The dimension of policy, regulatory and governance includes considerations related to monetary policy and financial stability effects as well as legal and supervisory frameworks and transition strategies. The study evaluates different CBDC regulatory approaches to identify best practices, while assessing the suitability of governance structures to maintain

financial stability and legal accountability. The analysis extends to examine how regulatory bodies work with national monetary authorities, financial institutions and technology service providers to promote innovation and stability in financial markets. The dimension of design and technology requirements concentrates on the technical requirements, interoperability standards, and product features necessary for successful implementations. The analysis encompasses factors such as security protocols, alongside scalability potential and interoperability concerns, considering the impact of the user experience for the acceptance process, while delivering specific recommendations for each area. The analysis examines the feasibility and implementation challenges of the technological solutions developed, including an identification of potential risks and benefits. The study evaluates how design and technological choices impact the overall effectiveness of CBDCs. The socio-economic and financial integration dimension evaluates CBDCs by examining their distribution models, societal acceptance, accessibility and the potential for international use. This dimension probes into the integration modalities of the CBDCs into international financial structures and the consequential effects. The necessary considerations for CBDC adoption encompass understanding their socio-economic impacts and identifying areas where resistance might occur, along with strategies to overcome such resistance and to determine the best ways to integrate digital currencies effectively. The concluding part of this study evaluates both environmental sustainability and inclusivity features while exploring their potential to benefit community development. The fourth dimension explores whether CBDCs could be sustainably designed and perceived as inclusive and beneficial for the community welfare. The analysis studies the environmental impact of CBDCs, their potential to improve financial inclusion and to find ways to make CBDCs accessible for everyone. The research aims to understand how CBDCs affect financial inclusion and economic stability, while examining how society accepts them along with their environmental impacts.

The objective of the first paper is to construct a comprehensive framework that combines multiple dimensions, to facilitate a complete understanding of CBDCs and their implications, as well as to identify the areas where future research could develop, providing a roadmap for researchers, policymakers, and individuals interested in CBDCs. To achieve its scope, the paper employs a critical literature review methodology to examine the existing body of knowledge on CBDCs. Through this methodology, the author gathered existing studies systematically, before assessing and combining the findings into a cohesive analysis. The data collection and analysis approach involved the identification of relevant studies, which required researching and selecting pertinent studies from primary sources, evaluating the papers to understand current knowledge levels, and combining findings from multiple studies to create a complete framework for CBDCs' assessment. Limitations identified by the author include

data availability issues and biases that emerge from the field's novelty, while findings' interpretation and inherent uncertainties may result from the lack of long-term data on CBDCs. The existing academic literature does not present a complete framework for understanding CBDCs' design, technical features and potential uses, which prevents thorough examinations of their effects on financial systems. This study contributes to bridge the gap in the literature, by developing an analytical framework for analysing the potential impact of CBDCs on financial systems, while also identifying future research paths for scholars, national monetary authorities and policymakers, and for those who wish to research CBDCs from consumer and business viewpoints. The suggested framework addresses several design and technical characteristics, together with their strengths and weaknesses as well as practical applications. The study enables a structured analysis of CBDCs' effects on financial systems, while drawing lessons from international collaboration and pilot project experiences, and it investigates how collaborative efforts between regulatory bodies, financial institutions, and technology service providers can support financial market innovation and stability. This paper provides the theoretical foundation upon which the other two papers elaborate.

The second paper, illustrated in Chapter 3, applies the framework elaborated, to perform a comparative analysis of three retail CBDCs. The currencies selected for the analysis are the Sand Dollar launched by the Central Bank of Bahamas, the eNaira established by the Central Bank of Nigeria, and the e-CNY established by the People's Bank of China. The research methodology adopted is a comparative case study of international experiences, that applies the comprehensive framework to analyse, assess, and compare the three retail CBDCs. The research questions addressed in this paper include how different CBDCs' implementations compare in terms of design, technology, and policy considerations; whether diverse CBDCs' implementations impact monetary policy, financial stability, and socio-economic integration in different ways; and what are the strengths and weaknesses of specific CBDCs. The research design includes the analysis of the three CBDCs, to detect shared themes and unique peculiarities, before addressing the findings with a complete overview of the three CBDCs. The methodology includes gathering information and data, about each CBDC's design choices, implementation processes, policy and regulatory frameworks, governance structures and institutional collaborations; analysing the design, evaluating the technological requirements; comparing the three CBDCs across different factors, highlighting their strengths and weaknesses. The paper considers how each country approached the implementation paths and what lessons can be learned, considering the specificities of the selected CBDCs; this offers a valid representation of possible scenarios that include simple, intermediate and advanced technical solutions, deployed across small, medium and large economies, and rolled out to segments of populations which are scattered across hundreds of islands, or

concentrated in big cities and rural areas, or impacted by an international diaspora. The framework adopted is designed to provide a comprehensive understanding of the three CBDCs by examining their implications across multiple dimensions. The analysis considers how each country addresses the four dimensions of the framework, with each dimension providing a different perspective on the implications of the three CBDCs, and what lessons can be learned, evaluating each CBDC, assessing their effectiveness, and identifying potential risks and benefits. The policy, regulatory, and governance dimension examines how each country addresses the monetary policy, financial stability, legal accountability, transition strategy, and regulatory oversight aspects and what best practices can be identified. The design and technology dimension explores the modernisation of payment systems, the security, the scalability, the user experience, the technology requirements, the interoperability and programmability potential of the three CBDCs. This dimension examines the technological challenges, and the systems developed for implementing CBDCs. The process requires an assessment of various technical solutions under consideration, along with feasibility assessments and potential risk-benefit evaluations. The socio-economic and financial integration dimension examines how these three CBDCs affect the financial inclusion together with the economic stability and societal acceptance levels. It includes the analysis of distribution models, adoption and usage, accessibility, and international use for cross-border transactions. The analysis examines the potential integration of each CBDC into the payment systems as well as their possible advantages and disadvantages. The research analyses the design criteria that enable each CBDC to operate sustainably, and an assessment of their potential to promote financial inclusion, and strategies for ensuring that CBDCs are inclusive and benefit all segments of society.

The research provides insights into effective policies for addressing contemporary economic challenges and offers recommendations and implementation guidance for policymakers and national authorities considering the implementation of a CBDC. This study examines implementation similarities and variations among the three countries, while evaluating the effectiveness of various approaches and identifying lessons learned along with best practices. This paper intends to fill a gap in the research gap, proposing a comparative analysis of CBDC implementations. Research often studies single CBDCs without comparing multiple types and their broader impacts. By comparing international experiences, the paper provides case studies and valuable insights into the strengths and weaknesses of different CBDC models and their implications for monetary policy, financial stability, and socio-economic integration, that complement the theoretical concepts discussed in the first paper.

The third paper, reported in Chapter 4, enhances the existing research on financial technology and digital currencies, by studying the integration of the asset tokenisation process with CBDCs, particularly focusing on the settlement of tokenised assets through CBDCs. The research questions that have been investigated for the third paper include the concept of lifecycle management of tokenised assets, the regulatory frameworks applicable for asset tokenisation, the role of CBDCs in settlement of tokenised assets, how can CBDCs improve financial markets processing, the contribution to the tokenised ecosystem, and how CBDCs compare to other digital currencies (tokenised deposits, stablecoins and crypto). The knowledge gap filled by this paper is related to the limited exploration of the relationship between the asset tokenisation process and CBDCs. Existing studies often overlook the potential benefits and challenges of integrating CBDCs with tokenised assets. This analysis evaluates the foundational principles of CBDCs for settling tokenised assets as well as their benefits and limitations, compared to other digital currencies. The study investigates the technological and regulatory components, evaluating multiple tokenisation frameworks, and explaining the rationale why CBDC should integrate with this technology. This paper advances the CBDC domain through a strategic analysis of the roles of digital currencies in the settlement mechanisms of tokenised assets. The paper examines the technical standards and regulatory requirements of asset tokenisation, alongside the CBDC settlement applications. This research investigates the differences between CBDCs and other digital currencies, such as stablecoins and cryptocurrencies, by evaluating their distinct features within the settlement processes of tokenised asset. The paper reviews the fundamental principles of the asset tokenisation process, including asset selection, platforms for asset tokenisation, for instance public blockchains (e.g. Ethereum, Stellar, Tezos) and private blockchains (e.g. Hyperledger Fabric, R3 Corda), and the lifecycle management of tokenised assets, including minting, issuing, distribution, trading, and settlement. The paper examines the effectiveness of the tokenisation processes, identifying challenges and opportunities for further research. The study assesses the body of knowledge and analyses the different regulatory approaches, to identify best practices along with technical standards and protocols necessary for the financial system integration. The analysis considers how different countries (i.e. the USA, EU, UK, Singapore, and Switzerland) approached the regulation of asset tokenisation, reviewing their effectiveness, and identifying potential risks and benefits, and what best practices can be identified. It examines the impact of regulatory choices on asset tokenisation. It also evaluates the technical standards and regulatory frameworks necessary for asset tokenisation. The analysis shows that CBDCs may serve as a critical component for enhancing digital assets' settlement processes, alongside potential challenges and solutions. The study is an exploratory research with case studies, aiming to investigate the new and evolving field of asset tokenisation and its implications for CBDCs. This includes the

identification of key themes and trends, and the synthesis of insights to develop a comprehensive understanding of the asset tokenisation process and its implications for CBDCs. The exploration of case studies is designed to provide a detailed understanding of the asset tokenisation process, by examining specific cases of tokenisation and settlement. The research evaluates the emergence of new financial products and services based upon tokenised assets, including innovative investment opportunities, decentralised finance (DeFi) applications, and more flexible and accessible financial instruments. The methodology includes collecting data, gathering information on tokenisation processes, comprising asset selection, platform choice, token creation, issuance and distribution, trading, analysing the standards' performance, evaluating the impact of tokenisation on settlements, including the technical and regulatory frameworks that govern these processes. These areas may be of particular significance in driving cross-border interoperability of tokenisation. The research indicates that stable and consistent regulatory frameworks are essential for successful deployment and cross-border compatibility of new digital technologies. The study recommends a collaborative regulatory approach between regulatory agencies, financial institutions and technology service providers, to develop an ecosystem that fosters financial innovation and regulatory compliance. Further studies on the regulatory landscape of asset tokenisation and CBDCs may help elucidate potential legal aspects and investor safeguards.

The paper offers an academic outline of a rapidly evolving field, by analysing recent research papers along with regulatory reports and industry surveys, available at the time of writing, to identify gaps in current knowledge and to assess the theoretical foundations. The paper integrates academic perspectives and recent research findings to evaluate both the advantages and challenges of tokenisation within financial systems. This paper demonstrates practical insights through the examination of case studies, with thematic analysis used to analyse qualitative data, allowing the author to detect recurring patterns, and insights. This study examines how CBDCs may become an enabler and complement tokenisation technologies and investigates how tokenisation may potentially improve the financial markets. The analysis encompasses the theoretical foundations of tokenisation, alongside empirical efficiency improvements, and CBDCs' case studies from current applications. The research analysed pertinent studies and the latest research papers from primary literature, authored by academic researchers, based on their journals' rankings in the Academic Journal Guide (Chartered Association of Business Schools, 2024) and from publications of international institutions i.e. Bank for International Settlements (BIS), World Bank (WB), International Monetary Fund (IMF), Financial Stability Board (FSB), along with national monetary authorities. This research has limitations due to the field's novelty, as researchers, industry actors and policymakers continue to explore this subject, while central banks, along with

international organisations, regularly release new contributions, leading to frequent developments that could drastically impact the current tokenisation processes and standards, and that may affect the study's conclusions. The creation of a tokenised market requires technical developments and the integration with existing payment infrastructure. Future research would benefit from a comparative analysis of suitable new technology and potential interface solutions with legacy financial systems. Real-world insights into the advantages and disadvantages of asset tokenisation and CBDCs may emerge from several pilot initiatives, across multiple organisations.

The three papers deliver an integrated study on CBDCs making valuable contributions to the fast-moving discourse in this field. The first paper examines the policy, regulatory, and governance structures of CBDCs to frame broader discussions on financial systems. The first study explores the socio-economic and financial implications of CBDCs, analysing their potential to modernise payment systems and to foster financial inclusion, offering access to financial services to marginalised populations. The research reviews possible design choices to analyse how CBDCs may address privacy and regulatory concerns. The second paper evaluates three retail CBDCs, their design and operational aspects, offering case studies and practical examples that demonstrate how different countries have implemented these principles and addressed these implications. The analysis focuses on a comparison between the retail CBDCs distributed by the Bahamas through the Sand Dollar, Nigeria through the eNaira, China with the e-CNY. The second paper applies the framework developed in the first paper by identifying the unique challenges and achievements of CBDCs, across the three countries and how different design and technology choices affect CBDCs' functionalities and user adoption. This analysis complements the theoretical framework established in the first paper as well as it provides practical recommendations for CBDC design and implementation, based on these experiences. The third paper addresses the underexplored area of asset tokenisation and its implications for CBDCs. The paper conducts an analysis of the potential integration of CBDCs for the settlement of tokenised assets, to enhance settlement efficiency, and to reduce intermediaries, while boosting market liquidity. The paper examines the technical standards for token issuance and management, as well as the regulatory frameworks necessary for asset tokenisation. It discusses how these standards and frameworks can be integrated with CBDCs to ensure efficient and secure transactions. Then the research compares and evaluate CBDCs against other digital currencies such as tokenised deposits, stablecoins and cryptocurrencies for settlement processes.

The three papers address respective gaps in existing research about CBDCs. The first paper establishes a detailed framework to examine CBDCs across multiple dimensions, advancing

CBDC research, by merging several factors that traditionally remain separate to deliver an all-encompassing analysis, which includes policy, technology, regulatory and governance perspectives, while discussing their potential effects on central banking functions. The second paper contributes to the literature, by presenting a comparative analysis of retail CBDCs, delivering insights about their design implementation and governance structures, and sharing practical implementation experiences from different countries, providing useful lessons and best practices. This study examines specific countries to understand their experiences with CBDCs, while identifying their distinct challenges, implementation outcomes and lessons learned. The third paper addresses the gaps in literature related to asset tokenisation and its integration with wholesale CBDCs. The paper provides comprehensive details about the transformation of traditional assets into digital tokens, and their settlement through CBDCs, which remains a relatively unexplored subject.

By presenting a unified body of knowledge, the three papers identify future research areas that may be explored to progress the understanding of CBDCs. The combined findings from the papers present essential insights and different perspectives for policymakers, researchers and practitioners, seeking to comprehend how CBDCs could transform the financial system.

CHAPTER 2. THE FUTURE OF MONEY: A COMPREHENSIVE FRAMEWORK FOR ANALYSING CBDCs

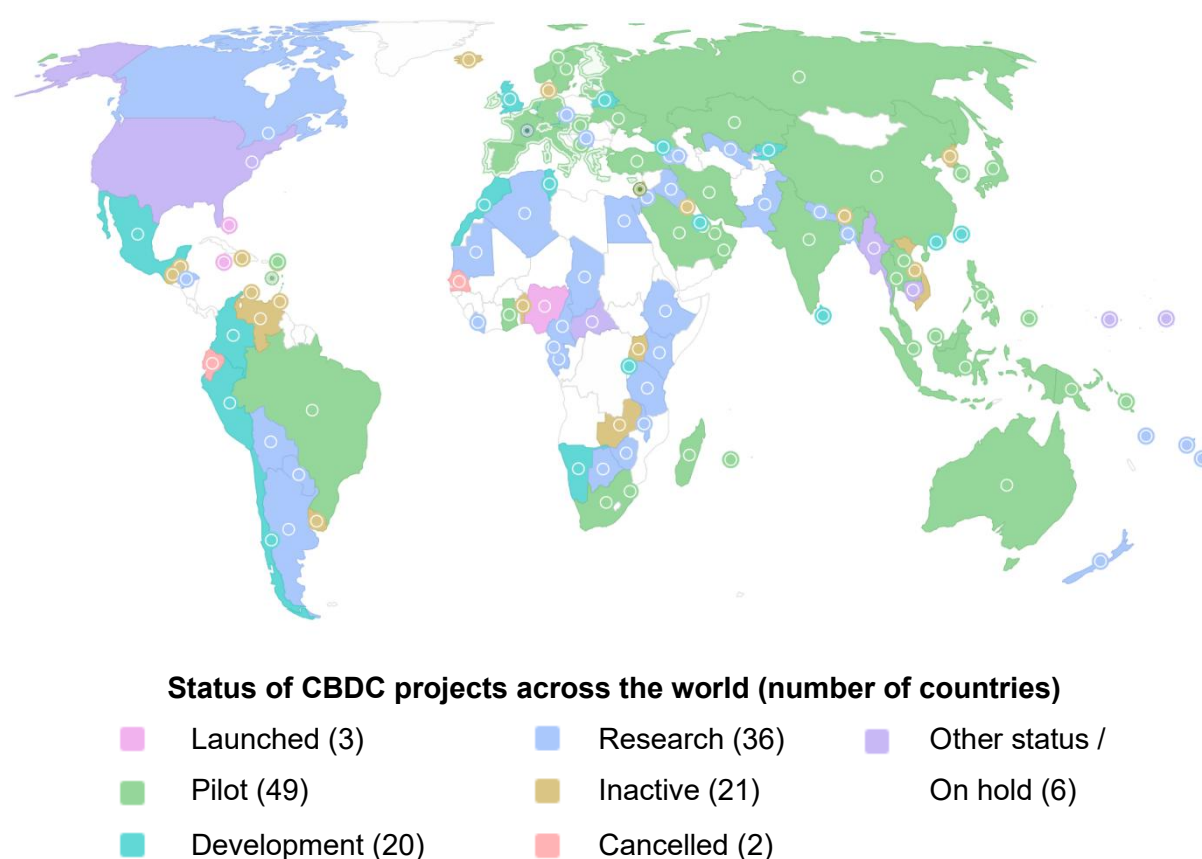
Money is an history of successful barter, from objects to metal commodities, from coins to banknotes and legal tender. The modern monetary system operates through fiat money, which represents a legal agreement that sovereign powers guarantee. The adoption of fiat currencies replaced commodity-based standards and enabled central banks and governments to gain better control of economic operations, through monetary policy instruments. Private digital currencies that operate in the modern financial system, compete against the existing payment infrastructure. The advent of cryptocurrencies (such as Bitcoin in 2009) established them as pioneers in digital currencies, providing new electronic payment methods, a way to store value and to speculate, leading to their acceptance by numerous users, as alternative for traditional state money. The crypto market experienced growth and volatility over the past decade and had a total capitalisation of 3.69 trillion USD on 23 October 2025 (CoinMarketCap, 2025a). Cryptocurrencies have gained broad acceptance however, authorities have become concerned about their impacts on monetary policy, sovereignty, consumer protection and financial stability. In response, national monetary authorities contemplate the implementation of central bank-issued digital currencies, as legal alternative to cryptos. Issued and operated by a country's monetary authority, CBDCs represent the third form of base money, along with cash in circulation and bank reserves, and could be adopted to modernise payment systems, to improve the efficiency of monetary policy transmission, and to support greater financial inclusion. Unlike cryptocurrencies, CBDCs combine the benefits of digital money with the trust, stability, and accountability of central bank electronic money.

At the same time, CBDCs present significant challenges. Concerns were recorded on the fear that CBDCs could disrupt the way bank deposits finance lending, thus reducing loaning and investment activities. Customers' orders to withdraw deposits to fund CBDCs digital wallets, could trigger for Banks the requirement to allocate, against reserves with the central bank, the same amount converted in CDBC digital wallets. Furthermore, the reduction of retail deposits may have an impact on the funding cost for banks, as to compensate the deposit withdrawals, financial institutions may be compelled to either draw down liquidity buffers, to increase interest rates to attract retail deposits, or to fund their activities through alternative sources (e.g. issuance of bonds). CBDCs may raise questions about privacy, cybersecurity, legal accountability, central banks' independence, and monetary sovereignty. The evaluation of systemic risks by central banks must be balanced against the technological advantages, while financial institutions need to assess market changes from new technologies, to create suitable

business plans. Successful deployments require resilient technical systems, governance structures and broad stakeholder engagement, tested through pilot programmes and informed by market feedback.

Central banks are experimenting with the new technology or are engaging in deployment projects around the world. Several national central banks are considering the implementation or working towards the release of their own CBDC, in the meantime, few CBDCs were launched worldwide. At the time of writing, there were 137 countries with CBDC projects initiated (Atlantic Council, 2025). Out of them, approximately 53% of the monitored countries progressed their projects through development stage (20 countries) or pilot phase (49 countries), and 3 projects were launched in their respective domestic markets. It is important also to note that 22% of the projects are either inactive (21 countries), or cancelled (2 countries), or in other status - on hold (6 countries). A visual representation of the different projects, along with their status per country is available in Figure 1.

FIGURE 1: INTERNATIONAL CBDCs BY STAGE OF DEVELOPMENT



Source: Central Bank Digital Currencies Tracker (Atlantic Council, 2025).

The interest for CBDCs by the global financial system is rooted in economic and institutional dynamics. The rationale for their introduction includes broader digitisation agendas, the efforts to reduce the informal economy, and the need to address inefficiencies in existing payment systems.

A CBDC functions as a digital currency and as a payment system, this dual role can reinforce national sovereignty in payments, by mitigating risks associated with reliance on international card processors (such as Visa, Mastercard, American Express, JCB, Discover, or UnionPay), traditional banks, and intermediaries (e.g. PayPal, Bizum). CBDCs offer a state-backed alternative to payment systems, in case of service disruptions or outages. CBDCs may deliver benefits for every transaction type, including cross-border payments, which experience high levels of inefficiency, due to the complex procedures, expensive charges and correspondent banking requirements. The implementation of CBDCs may simplify international transactions through instant payment processing, by removing the need for private networks, and by reducing transaction costs. A review of existing research provides useful insights into CBDCs' technological developments. Most research studies analyse CBDC topics independently, focusing either on technology, monetary policy, or regulatory aspects, without studying their combined effects. The current fragmented approach requires a comprehensive framework to provide a systematic understanding of CBDCs and their impacts on financial systems. The framework enables the evaluation of CBDC design elements systematically and provides policymakers, central banks, and industry stakeholders with tools, to understand their economic and institutional effects. Furthermore, a proper contextualisation and the analysis of long-term effects of CBDCs is absent, due to the novelty of the topic and to insufficient data depicting the impact of CBDCs over time, on a wide range of socio-economic indicators. Limited studies attempt to integrate these dimensions, which strengthens the case for this paper's contribution, i.e. the development of a comprehensive framework to guide research, policy, and practice in the evolving field of CBDCs.

This paper synthesises existing findings and highlights the strengths, weaknesses, and potential developments of CBDCs, by critically assessing the assumptions and arguments in the current literature. It reviews recent research and policy work from academic sources, international institutions and central banks actively engaged in CBDC design and experimentation. The paper delivers two key contributions, it introduces a comprehensive theoretical framework to explore the implications of CBDCs for financial systems, and it responds to a gap in the literature, where research has often been fragmented or siloed. Current literature explores distinct aspects of CBDCs, without integrating the dimensions into a cohesive analysis. This may prevent the holistic understanding of the systemic impacts of

CBDCs. Due to the novelty of the research domain and the limited availability of historical data, there is a lack of contextual and longitudinal studies that assess the long-term effects of CBDCs on a wide range of socio-economic indicators. There are limited comparative studies across CBDCs, with very few studies that attempt to integrate policy, regulatory, technological and social aspects, into a single evaluative structure, which can be very beneficial to understand the full implications and potential of CBDCs. The framework provides a structured tool for benchmarking implementation models and for conducting comparative case studies' analysis. The framework can become a tool for theoretical exploration and practical policy evaluation. The research offers recommendations for different stakeholders, including national monetary authorities, policymakers, financial institutes and technology providers. This may be valuable for policymakers and researchers seeking to understand the trade-offs and impacts of different CBDC design choices. The paper also identifies essential research areas for upcoming studies. The research provides readers with a detailed understanding of CBDCs, their design elements and economic functions, through the review of structured policies and industry discussions.

The research contains specific boundaries which need to be acknowledged. The paper develops a framework for analysing CBDCs, a research field that is subject to rapid change. The Executive Order from the White House (2025) which halted the CBDC development in the USA, is an example of unforeseen changes to the research environment. International organisations publish frequent research findings of pilot projects that advance the knowledge in this field (e.g. BdF, BIS and SNB, 2021). The analysis faces limitations, as a limited number of countries have implemented CBDCs, with researchers lacking access to extended historical data, which creates challenges in analysing the operational scenarios and in understanding the CBDCs' effects on financial systems.

2.1. THEORETICAL FRAMEWORK

A CBDC is fiat money in digital form issued and controlled by a national central bank or other national monetary authority. It is an integral part of the country's monetary policy, with similar attributes to other typologies of money (Bordo and Levin, 2017). CBDCs are a form of legal tender backed by a country, the expected core traits foresee a centralised approach, and the possibility, through authorised financial intermediaries, to interchange with traditional money, albeit remaining separate from it (BIS et al., 2020). By contrast, cryptocurrencies are decentralised and self-governing digital assets, and they do not represent legal tender, although they may be pegged to existing currencies (e.g. stablecoins). As digital alternative to cash, CBDCs benefits from the speed, convenience, and security of electronic payments,

mitigating counterparty default risk associated with banks, price volatility and the regulatory uncertainty of privately issued cryptocurrencies.

The framing features of CBDCs seem to have broad international consensus between monetary authorities. In terms of sovereign issuance, CBDCs inherit the same trust and value as traditional fiat currencies, discriminating them from private digital currencies. CBDCs represent a unit of account, a medium of exchange, and a store of value (Ardic, Oya & Bossone, 2021). CBDCs possess the status of legal tender within the issuing country, meaning they must be accepted for the settlement of debts and payment transfers. CBDCs exist in digital format and are stored on a ledger, managed by a designated entity. The fact that CBDC are not tangible, represents the key difference from cash or coins. Their programmability may enable embedded compliance with legal and regulatory frameworks, behavioural restrictions, or novel applications in monetary policy. CBDCs represent a unique category, as they retain the security and the legal tender status of cash, but they leverage technology and the other benefits of digital money. In table 1, a summary of the key characteristics of digital currencies is represented.

TABLE 1: DIGITAL CURRENCIES' FEATURES

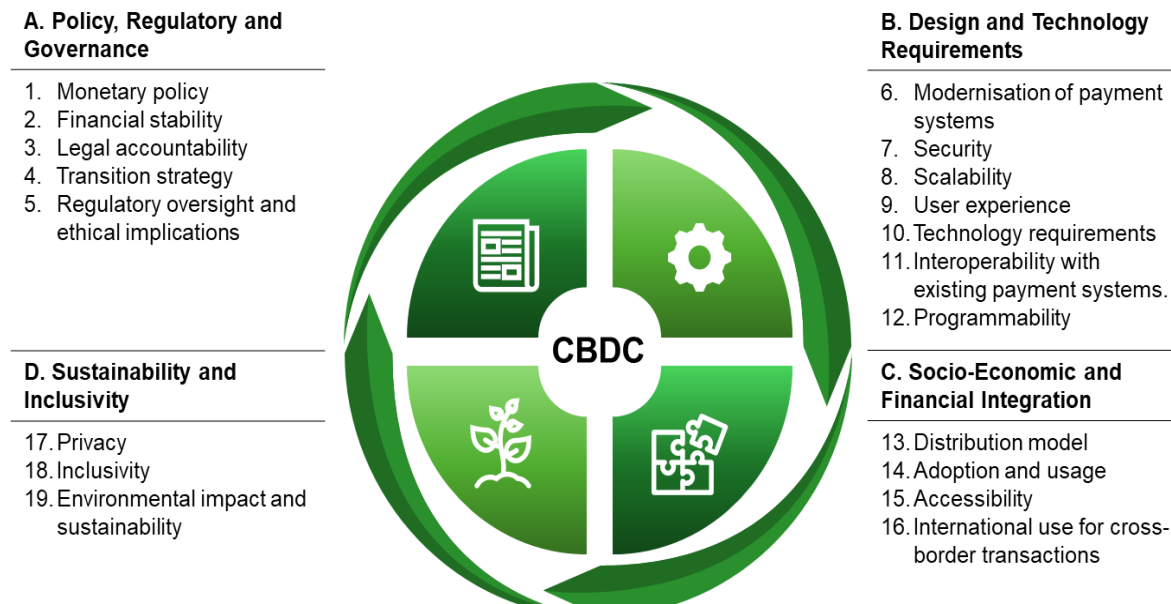
Type of Currency	Issuer	Form	Legal Status	Risk
Crypto	Decentralised digital assets, self-governing.	Digital tokens not pegged to assets.	No legal status (except for Bitcoin in El Salvador, where it was legal tender between 2021 and 2024).	No lender of last resort, market risk, cyber risk, regulatory risk, liquidity risk, operational risks, systemic risks.
Stablecoins	Private companies.	Digital assets backed by fiat currencies, commodities, other assets or cryptos.	The applicable regulatory frameworks show significant material differences between these financial instruments mostly because they incorporate e-money principles or asset-referenced token features.	Several risks including credit, market (loss of peg), liquidity, cyber, operational, systemic, and interoperability risks.
Commercial Bank Money (including tokenised deposits)	Licensed financial institutions.	Electronic money (Deposits). E-money tokens (Tokenised Deposits).	Issued following banking laws and crypto regulatory frameworks.	Credit risk, liquidity risk, operational and interoperability risks.

Type of Currency	Issuer	Form	Legal Status	Risk
CBDCs	Central Banks.	Digital Central Bank money.	Legal tender.	None (direct claim on central bank).
Cash	Central banks.	Physical currency.	Legal tender.	None (direct claim on central bank).

Source: Author's elaboration.

A theoretical framework can be beneficial for classifying CBDCs, consolidating relevant factors into coherent thematic dimensions. Such a framework can serve as a comparative analytical tool to benchmark CBDC implementations, drawing on insights and debates from current literature. The framework is informed by academic work, policy reports, and recent survey data from central banks and international institutions. Several elements were assessed to discern their suitability for the inclusion in the framework, namely: monetary policy; financial stability; legal accountability; transition strategies; regulatory oversight and ethical implications. Other areas analysed are the modernisation of payment systems, security, scalability, user experience, technology requirements, interoperability with existing applications, programmability, distribution models, adoption and usage, accessibility, cross-border functionality. Complex aspects like privacy, inclusivity, and environmental sustainability were included in the analysis. All factors may be grouped in four dimensions, as presented in Figure 2: (A) policy, regulatory, and governance; (B) design and technology requirements; (C) socio-economic and financial integration; and (D) sustainability and inclusivity.

FIGURE 2: THEORETICAL FRAMEWORK FOR ASSESSING CBDCs



Source: Author's elaboration.

Each dimension includes interrelated variables, which facilitates the controlled assessment of CBDCs across jurisdictions. The clustering contemplates recent academic and policy analyses that emphasise the multifaceted nature of CBDCs. The four dimensions encompass a wide range of equally important variables, detailed as follows:

- A. Policy, Regulatory and Governance.** This dimension covers monetary policy, financial stability, legal accountability, transition strategies, regulatory oversight, and ethical implications. Bindseil (2020) and Adrian and Mancini-Griffoli (2021a) argue that the CBDC design is not primarily a technological matter but most importantly a financial and regulatory decision. CBDCs require the integration within an appropriate regulatory framework, to support monetary policy objectives and to maintain financial system stability. The strategy for transitioning from existing fiat and electronic payment models to CBDCs would significantly influence the user adoption and could help to mitigate systemic risks. The essential role of regulatory oversight lies in guaranteeing compliance, while reducing illegal transactions and protecting consumer rights, as identified by the BIS et al. (2024).
- B. Design and Technology Requirements.** This dimension includes variables such as modernisation of payment systems, security, scalability, user experience, technology requirements, interoperability with existing payment systems, and programmability. The rationale for grouping these aspects rests on the recognition that the technical architecture

of a CBDC underpins its operational viability. Central banks' experiences demonstrate that selecting between Distributed Ledger Technology (DLT) or centralised ledgers may affect the scalability and interoperability aspects of CBDCs, according to Boar and Wehrli (2021). The research into programmability connects directly with current studies about smart money capabilities, including conditional payments (Leucci, Attorelli and Lareo, 2023).

- C. **Socio-Economic, Financial Integration factors.** This dimension integrates variables such as the distribution model, adoption and usage, accessibility, and international use for cross-border transactions. Research findings confirm that consumer trust and convenience, together with accessibility, may determine how widely CBDCs are used, according to the BIS, CPMI and MC (2018) and the IMF (2023). The distribution method chosen for CBDCs affects accessibility, with direct and hybrid models (using financial intermediaries) delivering different levels of convenience to various population segments. The possibility of CBDCs to lower cross-border transaction costs, alongside increased speed and transparency, while potentially establishing new international arrangements, has been evidenced in recent BIS studies (Auer, Haene and Holden, 2021; Carstens, 2021).
- D. **Sustainability and Inclusivity.** This dimension contains privacy, inclusivity, environmental impact, and sustainability. While CBDCs' studies initially focused on technical aspects, current research also explore privacy and data protection (Murphy et al., 2024). Consumers need assurance that transaction data remains secure from misuse and violations. Experts debate the prevention of discrimination and seek methods to enhance financial inclusion through CBDC, while examining principles of fairness in data ethics. The environmental footprint of CBDCs is a relatively new research field, which emerged due to the global commitments to sustainability and carbon neutrality.

The four dimensions offer a solid basis for comparative analysis across jurisdictions. In the next chapter, the variables are analysed in detail, critically reviewing the different perspectives, advanced in the academic and policy literature.

2.2. CBDCs' DESIGN CHOICES AND THEIR IMPLICATIONS FOR FINANCIAL SYSTEMS

In this section, the possible design choices for CBDCs are analysed along with their broader implications for financial systems. The study considers how different architectural, technological, and governance models may influence monetary policy, financial stability, payment efficiency, and market structure. Research indicates that growing public knowledge about CBDCs exists, while consumer trust shows mixed responses, due to data privacy concerns and uncertain regulatory frameworks (BIS, 2019). To support the analysis, a multi-criteria evaluation framework is proposed to operationalise the variables within the four dimensions. The framework combines technical standards with policy objectives as well as social, regulatory, and environmental factors, and it highlights the trade-offs inherent in CBDC design, reflecting the cross-disciplinary nature of CBDC research and practice, and enabling systematic cross-jurisdictional comparison of projects. For instance, privacy safeguards may limit regulatory compliance. The proposed framework is illustrated in the table below.

TABLE 2: OVERVIEW OF THE FRAMEWORK FOR ASSESSING CBDCs

Dimension	Factors	Critical Actions	Attention Points
(A) Policy, Regulatory and Governance	1. Monetary policy	Integrate CBDCs within existing monetary frameworks.	Balance strict regulation with space for innovation.
	2. Financial stability	Define interest and remuneration policies.	
	3. Legal accountability	Prioritise financial stability safeguards.	Address risks of bank disintermediation and financial stability.
	4. Transition strategy	Strengthen and adapt legal frameworks.	
	5. Regulatory oversight and ethics	- Identify transactional and digital wallet holding caps. - Plan gradual rollouts and pilot phases. - Gather public feedback during transition. - Clarify regulatory oversight responsibilities.	Regulatory frameworks should limit data retention, and access. Independent oversight to monitor for abuse.
(B) Design and Technology Requirements	6. Modernisation of payment systems	Ensure freedom of choice for payments.	Evaluate adjustments required among scalability, cybersecurity, and user experience requirements.
	7. Security	Implement state-of-the-art security to build public trust.	
	8. Scalability	Cooperate with international bodies on feasibility studies.	
	9. User experience		Assess execution speed and

Dimension	Factors	Critical Actions	Attention Points
	10. Technology requirements	Launch consultations on user experience design.	validation methods.
	11. Interoperability	Develop resilient solutions within local constraints.	
	12. Programmability	- Ensure interoperability through trial programs. - Embed programmability for future policy tools.	
(C) Socio-economic and Financial Integration	13. Distribution model	Foster adoption rates with the support of banks, merchants, and financial institutions.	- Balance accessibility with infrastructure costs. - Consider geopolitical motivations with national priorities.
	14. Adoption and usage	Promote awareness and educational campaigns.	
	15. Accessibility	Ensure usability and trust.	
	16. International use	- Collect feedback from stakeholders. - Support integration with international systems.	
(D) Sustainability and Inclusivity	17. Privacy	Embed privacy safeguards.	- Balance privacy rights with AML/CFT compliance. - Meet sustainability goals without compromising efficiency.
	18. Inclusivity	Implement data governance.	
	19. Environmental impact	- Create a shared communication plan with all stakeholders. - Prevent misuse of data access. - Promote financial inclusion initiatives. - Adopt energy-efficient designs and technology.	

Source: Author's elaboration.

The following sections investigate the technological developments, current research and scholarly debates, related to the CBDCs' design choices and implementation experience.

A. POLICY, REGULATORY AND GOVERNANCE

This section analyses the first of the four dimensions. By engaging with recent academic and policy debates, the paper ascertains areas that might impact the design and implementation of CBDCs.

2.2.1. MONETARY POLICY

The implementation of CBDCs creates significant effects on monetary policy operations. The main challenge emerges when central bank liabilities, with interest-bearing features, compete against commercial bank deposits (BIS, 2021). CBDCs may enable better, systematic and transparent policy execution, according to Bordo and Levin (2017). Meaning et al. (2021) informed that CBDCs may modify the way monetary policy operates, improving the transmission mechanism. The status of legal tender enables central banks to distribute policy changes to households and firms, strengthening interest rate adjustments and stimulus measures (Davoodalhosseini, Rivadeneyra and Zhu, 2020). The implementation of CBDCs may create new risks that could produce unintended consequences. Retail CBDCs might create bank disintermediation risks during periods of financial turmoil (Das et al., 2023). The introduction of CBDCs might lead to exchange rate volatility and the creation of liquidity traps that may generate substantial economic losses. CBDCs requires a thorough design and a strategic implementation planning to achieve optimal results.

2.2.1.1. EXCHANGE RATE REGIMES

The existing exchange rate system impacts how a CBDC functions. A free-floating exchange rate system allows markets to determine exchange rates and grants central banks full control over money supply and interest rates (Mishkin, 2009). The ability to adjust interest rates on digital CBDCs' balances enables central banks to achieve faster policy implementation (BIS, 2022b). This system is effective at handling external shocks, as central banks may use expansionary or contractionary policies without currency peg constraints (Bordo and Levin, 2017). Despite the system's ability to manage external shocks, exchange rates become more volatile, demanding strong risk management systems that align with financial stability goals. The main goal of monetary policy, in pegged or managed exchange rate systems, focuses on maintaining exchange rate stability. The implementation of CBDCs enhances transaction speed but does not change the requirement for sufficient anchor currency reserves, to maintain exchange rate stability. Digital currencies enable fast capital movements which create reserve shortages and make countries more susceptible to international spillovers of shocks, according to Patel, Reshidi and Reuter (2025). The implementation of design elements such as transaction limits, multi-level wallet systems, digital wallet holding caps, and monitoring systems may reduce risks at the cost of restricting the free movement of funds (Patel, Reshidi and Reuter, 2025). The Bahamas implemented the Sand Dollar under a pegged system, while China tested its digital renminbi through a managed float system. The use of pegged exchange rates provides stability through currency anchoring but restricts

monetary policy flexibility and it reduces the operational range of CBDCs. The assessment of CBDC feasibility depends heavily on the selection of exchange rate regimes, which should be regarded as one of the primary design considerations.

2.2.1.2. INTEREST RATE POLICY

The academic debate on interest rate policy for CBDCs focuses on two main points, their necessity and the appropriate methods for implementing positive and negative rates, to enhance monetary policy effectiveness. Central banks can use interest rates on CBDC accounts, to steer users toward saving or spending attitudes (Davoodalhosseini, 2022). The implementation of positive interest rates on CBDCs would drive users to replace cash with digital wallets, while negative interest rates might boost consumer spending during economic downturns, by overcoming the zero lower bound. The implementation of interest-bearing CBDCs would strengthen conventional monetary tools, as they create a faster path for central banks to reach businesses and individuals (Bindseil, Panetta and Terol, 2021). However, the implementation of interest-bearing CBDCs faces multiple operational obstacles. The adoption of interest-bearing CBDCs could enable users to move their funds from traditional bank deposits to digital currency accounts, which may reduce bank lending capacity and potentially constraining economic growth (Caccia, Tapking and Vlassopoulos, 2024). The combination of disintermediation risks with unclear public benefits from negative interest rates demands careful implementation strategies. The current infrastructures may not yet support interest rate differentiation on digital accounts, creating potential risks for the financial system (Meaning et al., 2021). The implementation of interest rates on CBDCs expands monetary policy tools but experts remain uncertain about both its technical feasibility and its effects on the economy. The academic literature shows diverse opinions about implementing interest rates for CBDCs. The implementation of interest-bearing CBDCs may enhance monetary policy effectiveness, as they establish a direct financial connection between central banks and digital wallet holders (Bordo and Levin, 2017). The implementation of positive interest rates on CBDCs would draw cash users toward CBDC wallets, while negative interest rates would give central banks a new tool, to boost spending during economic downturns. The implementation of CBDCs offers three main advantages, which include better policy incentive precision, seigniorage revenue preservation, and expanded financial inclusion (Patel, Reshidi and Reuter, 2025). The implementation of interest-bearing CBDCs faces opposition, due to the potential disintermediation risks to the existing banking system. The transfer of deposits from commercial banks to CBDCs might lead to reduced lending capacity and economic growth problems. The management of financial stability risks together with privacy and transparency issues requires effective governance frameworks (Das et al., 2023). CBDCs with interest-

bearing features requires technical expertise, dedicated policies and pilot program data, to validate theoretical models with practical evidence.

2.2.2. FINANCIAL STABILITY

Through their innovative features, CBDCs may inadvertently lead to unforeseen consequences on financial stability. Central banks issue CBDCs to achieve several objectives which vary from financial inclusion to macroeconomic stability and enhanced monetary policy effectiveness (Fung and Halaburda, 2016). The combination of attractive interest rates and simple fund transfers into CBDCs may facilitate flight-to-safety behaviour during crisis situations (Bouis et al., 2024). The perception that CBDCs offer superior safety than bank deposits and the absence of CBDC digital wallet caps, may lead users to move funds into their CBDC wallets in times of crisis, depleting commercial bank deposits and leading to credit shortages and banking system instability (BIS et al., 2021b). The adoption of CBDCs has the potential to reduce traditional banking revenue from payment services, which could decrease banks' profitability and their ability to support real economic activities. Multiple design solutions exist to reduce the potential risks that CBDCs present. The implementation of tiered interest rates for CBDCs which pay no interest or minimal interest beyond specific balance limits, may prevent large-scale bank deposit withdrawals (Bindseil, 2020). The implementation of transaction and digital wallet holding limits may function as a risk management tool, to prevent disintermediation, by restricting both balance limits and transfer amounts. The combination of these tools with proper CBDC design parameters enables financial stability protection, while maintaining digital money efficiency, according to Meaning et al. (2021).

2.2.3. LEGAL ACCOUNTABILITY

An appropriate legal framework enables CBDCs to gain public trust and to drive user adoption. The legal tender status, together with the independence of central bank, and user privacy regulations identify both opportunities and risks of CBDCs' implementation.

2.2.3.1. LEGAL TENDER STATUS

The legal status of CBDCs is central to their public acceptance. The system requires legal recognition of central bank electronic money to function as payment instruments that resolve financial obligations and execute payment operations. The legal tender status of CBDCs may enable citizens and businesses to use digital currencies as payment tool, enhancing their status as standard exchange medium. CBDCs may enhance payment speed, decrease cash

management expenses and enable digital payment solutions for underbanked and unbanked groups of people (Bindseil, Panetta and Terol, 2021). The use of CBDCs as legal tender may encounter operational challenges during implementation. The mandatory acceptance may create concerns to vulnerable people, small businesses and low-income groups or residents in remote areas, as digital infrastructure gaps might exacerbate existing social inequalities (Auer et al., 2022). CBDCs demand broad legal changes to currency laws, payment systems and financial regulations, which may lead to prolonged and complicated procedures (Bossu et al., 2020). A phased legal strategy that implements reforms through sequential placement, would minimise these risks, by allowing smoother transition process.

2.2.3.2. CENTRAL BANK INDEPENDENCE

Granting to CBDCs the legal tender status may have an impact on central bank independence. The implementation of CBDCs would give central banks a more direct control over monetary policy, however it would simultaneously increase their vulnerability risks to political interference. Governments might force central banks to implement CBDCs for quasi-fiscal operations that may include digital helicopter money transfers to households, thus obfuscating the distinction between monetary and fiscal policy. Furthermore, the implementation of CBDCs by authoritarian governments may destabilise central banks' independence, leading to potential threats to monetary policy.

2.2.4. TRANSITION STRATEGY

The transition from cash to CBDCs demands detailed planning, a step-by-step execution, together with effective information sharing. The academic debate focuses on the optimal pace. Advocates of gradualism emphasise risk reduction and inclusivity benefits, as digital literacy and access disparities have the potential to generate fresh social inequalities, according to Boakye-Adjei et al. (2023). A controlled deployment, supported by coexistence with cash and tools such as tiered remuneration schemes, may mitigate the risks of bank disintermediation and operational disruption (Bindseil, 2020). By contrast, others emphasise the urgency of rapid adoption to match technological change and counter the dominance of private cryptocurrencies (Berentsen and Schär, 2018). However, accelerated transitions may disregard the current state of infrastructure readiness, and the need for public education programs. The selection between token and account-based models in technological design affects user adoption because it establishes system accessibility, and it impacts user experience and security levels (BIS et al., 2021a). The development of trust and user adoption depends on effective awareness strategies, which experts recognise as fundamental

organisational elements. Research evidence indicates that central banks need to adopt clear communication strategies which reveal their plans and adapt to national economic conditions (BIS, 2019). Public education campaigns should focus on digital literacy to bridge the gap, while businesses and stakeholders need direct engagement, to understand goals and to receive iterative feedback. The implementation process may receive additional support from private intermediary partnerships, which may also enhance system interoperability. Implementations through phased approach allow the possibility to perform country-specific adjustments in transition strategies, mitigating risks and enhancing the public acceptance of CBDCs.

2.2.5. OVERSIGHT AND ETHICS

Regulatory and ethical aspects represent important areas of research for CBDCs, in consideration of the potential impact on financial systems of privacy concerns, governance challenges and supervisory control issues that may arise during the implementation phase.

2.2.5.1. REGULATORY CHALLENGES

The implementation of CBDCs requires fresh regulatory oversight, as existing rules were developed for a pre-digital currencies' system. The direct provision of services to people by CBDCs creates challenges for financial stability, monetary sovereignty and central bank identity, as, depending on the design choices, they might combine central banking operations with retail banking functions (Söderberg et al., 2022). The BIS et al. (2021b) indicate that financial stability needs compliant regulatory systems to prevent criminal activities. AML and KYC systems, with defined intermediary roles and monitoring tools, must be implemented to enable central banks to track risks, while maintaining public trust (Wang and Gao, 2024). However, the establishment of excessive rules would undermine financial innovation, while it would also block the benefits that financial inclusion and productivity growth may provide (BIS et al., 2021b).

2.2.5.2. ETHICAL CONCERNS

The implementation of CBDCs generates new ethical problems which extend past the necessary requirements for compliance. The traceability and programmability of digital currencies could, under certain conditions, enable governments to steer consumer behaviour or restrict transactions, in pursuit of policy goals. The implemented features may enable fraud prevention and activity monitoring but may also create privacy problems and surveillance

issues in nations with limited democratic freedoms. Through tiered privacy systems, users can remain anonymous for small transactions, yet they would be obliged to authenticate for larger transactions, to fulfil regulatory requirements (Murphy et al., 2024). Public acceptance of CBDCs depends on privacy protection as an essential requirement.

2.2.5.3. GOVERNANCE AND INTERNATIONAL COORDINATION

The implementation of CBDCs may generate fresh governance challenges. As mentioned, the application of interest rates by central banks to digital wallets could create negative perceptions about state control and blur distinctions between monetary and fiscal policy functions. The combination of regulatory frameworks, with cybersecurity measures and consumer protection protocols, may support the development of international CBDC standards, improving the resilience and ensuring interoperability and trust between jurisdictions. International regulatory bodies should be tasked to identify potential misuse cases, to ensure protection to individual rights from unethical exploitation.

B. DESIGN AND TECHNOLOGY REQUIREMENTS

Indications of the CBDCs' viability, resilience, and sustainability may be inferred by their design and architecture choices. Consideration should be given to several elements, including the modernisation of payment systems, cybersecurity, scalability, interoperability, as well as programmability and user experience. The design choices may influence how CBDCs function and their ability to fulfil policy objectives, to interface with existing systems and to adapt to future technological developments. The following sections examine essential design elements, together with their implications on central banks, financial systems and end users.

2.2.6. MODERNISATION OF PAYMENT SYSTEMS

CBDCs are widely viewed as a response to ongoing digital disruption in finance, with the potential to increase transaction speed, reduce costs, and simplify settlement processes. By removing intermediaries, CBDCs enables fast payment processing and immediate transaction settlement, which increases the reliability of financial operations, according to the BIS et al. (2020). Advocates of CBDCs point to their capability to transform cross-borders payment systems through unified networks, which may cut out correspondent banking chains for faster processing and lower costs (World Bank, 2021). The Chinese e-CNY program demonstrated that centralised CBDC systems can execute fast and secure transactions at scale (PBoC,

2021). The implementation of CBDCs may increase efficiency and transparency of payment systems. CBDCs may process transactions in real time, enabling regulators to detect payment activities, decreasing fraud and corruption risks, while preventing tax evasion. Improved monitoring could strengthen the integrity of the financial ecosystem while supporting public trust. Through partnerships with fintech companies, the creation of inclusive financial solutions, through mobile payment systems and alternative platforms, may offer financial services to the underbanked and unbanked groups of population (Auer et al., 2022). However, risks remain. In case of retail direct distribution models, the implementation of CBDCs may allow people to store their money directly in central bank digital wallets, potentially reducing commercial bank deposits and the ability for banks to provide credit, financing the economy (BIS et al., 2021b). A scale (e.g. small, medium and low) may be applied to this variable, to assess the level of transformation that CBDCs may bring to existing payment systems. Users' trust depends on the proper implementation of digital currencies, which require to maintain equilibrium between privacy and cybersecurity requirements. Research shows that successful implementation depends on proper deployment, strong protective measures and joint governance between central banks, policymakers, technology providers and international organisations.

2.2.7. SECURITY

The security of CBDCs needs to be based on appropriate design, as digital currencies experience ongoing threats from cyberattacks, operational failures and fraudulent activities. The combination of sensitive financial information with centralised infrastructure in CBDCs makes them vulnerable to potential breaches, which may damage trust and create widespread financial instability (BIS, 2023g). Digital asset protection depends on three essential elements which consist of cryptographic security measures, authentication protocols, and sustained support for digital security systems (BIS et al., 2021a).

2.2.7.1. CYBERSECURITY AND OPERATIONAL RISKS

The digital nature of CBDCs exposes the digital currencies to potential hacking attacks, system failures and unauthorised data breaches (Murphy et al., 2024). A centralised CBDC system creates vulnerability through its single point of failure, however distributed ledger technology adopted by decentralised systems may struggle with scalability issues. Multi-factor authentication, role-based access controls, back-up redundancy and real-time monitoring systems may represent effective security measures. In case of major disruptions, business operations depend on contingency planning measures, to ensure operational resilience.

Furthermore, programmable features of CBDCs through smart contracts, might introduce new vulnerabilities and require rigorous code auditing and monitoring, to avoid systemic disruptions. Business continuity management requires organisations to establish backup and redundant systems, to ensure continuous availability during system failures and cyberattacks. The implementation of appropriate legal frameworks for the management of cyber threats serves as an essential requirement for successful cyber incident response. The implementation of standardised procedures for incident management, remediation and international cooperation may support public trust in CBDCs, during adverse operational conditions (BIS, 2023g).

2.2.7.2. DESIGN CHOICES: TOKEN VS. ACCOUNT MODELS

A central security question is how ownership is verified. Token-based systems function similarly to cash systems, as users holding tokens can manage them anonymously, enhancing financial accessibility, according to the BIS, CPMI and MC (2018). The adoption of digital currencies may introduce security threats, resulting in thefts and losses and facilitating criminal activities (BIS, 2023g). The implementation of account-based systems, which confirm asset ownership through identity verification, enhances both regulatory adherence and asset retrieval, yet these systems may pose entry barriers to unbanked people for accessing financial services, while making them vulnerable to monitoring transactions (Auer et al., 2022).

2.2.7.3. TECHNOLOGICAL FRONTIERS

The implementation of blockchain technology in CBDCs may enable the creation of resilient systems, thanks to the removal of single points of failure and the establishment of permanent transaction records. This type of systems may face scalability issues, when used at a large retail scale, as centralised models may operate more efficiently despite their potential exposure to major system breaches. The development of new technologies brings several challenges, for instance quantum computing systems have the potential to break existing encryption methods, according to Aggarwal et al. (2017), but they may also enable faster transaction processing. Quantum-resistant algorithms, along with advanced cryptographic methods and zero-knowledge proofs, may be useful tools to ensure protection from security risks for CBDCs' applications (Azimi et al., 2025). Further research may be conducive to identify commercially viable solutions.

2.2.7.4. GOVERNANCE AND INTERNATIONAL COORDINATION

The operation of technology processes necessitates governance mechanisms to ensure positive outcomes. Effective procedures require the development of response protocols for cyber breaches, while international organisations need to establish uniform security standards for CBDCs' interoperability. The implementation of privacy protection systems requires policymakers to establish a balance between data confidentiality, oversight functions and national security needs. The detection of future threats depends on ongoing collaboration between central banks, regulators and technology providers to protect public trust.

2.2.8. SCALABILITY

The successful implementation of CBDCs depends on their ability to handle rising transaction volumes, while maintaining both security standards and operational performance. A system would need to manage transaction growth and high-performance workloads, by adding resources efficiently, when demand increases (BIS and SNB, 2023). The servicing of retail CBDCs requires systems that may be able to process high transaction volumes, entailing low-latency settlement and high throughput. Public trust in CBDCs may be impacted by delayed transaction verification processes, while systems may become vulnerable to cyberattacks and face systemic risks, in case of poor design choices (Bulgakov et al., 2024; Brownworth Anders et al., 2022). A central debate in the literature concerns whether CBDCs should rely on centralised infrastructures or DLT technologies. Proponents of centralised systems (Auer, Cornelli and Frost, 2020) argue that their track record in current interbank settlement operations, their cost-efficient solutions and regulatory compliance capabilities. The implementation of centralisation creates both system vulnerabilities through single points of failure and privacy risks (Ballaschk and Paulick, 2021). DLT systems may provide transparency, resilience and immutability, but its scalability is uncertain. The current blockchain technology systems encounter problems with its ability to scale and process transactions efficiently. Studies highlight that block size increases can reduce decentralisation (Croman et al., 2016), and blockchain in its current form may be unsuitable for national-scale payment systems (Casey et al., 2018; Peters and Panayi, 2016). Recent studies identify three upcoming solutions which include permissioned blockchains, proof of stake protocols and secure consensus algorithms, to boost system performance, though limitations in consensus mechanisms persist. Hybrid models combine core operations under centralised control, with distributed verification systems and token-based methods, to resolve trade-offs. Systems may improve operational efficiency and scalability, while maintaining regulatory control, according to Auer and Böhme (2020). The deployment of CBDC systems may result in operational

difficulties, with the introduction of new operational threats, according to BIS et al. (2021a). Improvement to the transactions volumes and processing speeds should be assessed against the operational complexity, technological requirements and cyber resilience vulnerabilities that they may introduce. A risk-management approach to scalability, that considers the technology choices involved, seems to be the most suitable way forward.

2.2.9. USER EXPERIENCE

The academic debate on CBDC focuses on technology and economical aspects. Although user experience and interface design play an essential role in adoption, many researchers did not fully examine these aspects. A user interface (UI) that is easy to understand and secure, functions as the primary entry point for people and organisations and determines how well users accept and adopt CBDC wallets (Auer and Böhme, 2021). Simplicity in systems reduces entry barriers and enables users to develop trust, supporting people with basic digital skills to access new technology (Auer et al., 2022). CBDC user interface systems need to support underbanked people, low-income groups or residents in remote areas and users with disabilities, to achieve accessibility and inclusivity (Boakye-Adjei et al. 2023). The integration of CBDCs into current payment applications may enable smoother adoption and may decrease public opposition to new payment systems, according to BIS (2021). The BIS (2019) surveys show that users consider simple interfaces to be vital for CBDC adoption. CBDCs need to achieve both usability and security standards. Easy access systems that require minimal entry barriers, result in increased user adoption rates however, these systems may create security risks for users, due to potential fraud and data breach exposure (BIS, 2023g).

The trustworthiness of CBDCs depends on user-friendly interfaces and robust security measures. The design process needs strategic decisions about these trade-offs, according to the BIS et al. (2021a). Auer, Cornelli and Frost (2020) advocate for working with private technology providers, to achieve innovation and reach diverse population segments. The academic literature suggests that user interfaces should be accessible, secure and inclusive, but it does not provide effective methods to achieve these objectives. Future research may examine social aspects of UI, by analysing design elements that affect user trust, long-term adoption and financial inclusion. The implementation of CBDCs requires a multidisciplinary team consisting of technologists, economists and social scientists to fulfil the requirements of diverse user populations.

2.2.10. TECHNOLOGY REQUIREMENTS

The literature provides a range of views on the different technological solutions that could support the implementation of CBDCs. The creation of an appropriate technical infrastructure, ready to support the daily CBDCs' operations, would be the first step to ensure the processing of transactions in real time, the seamless integration with existing financial applications and the tracking of data for compliance purposes (Auer, Cornelli and Frost, 2020). However, this requires considerable investments and the setup and maintenance of sophisticated platforms to ensure the transactions' processing. As per each technological component, the regular cycle of upgrades and security patching, and the periodical scaling of the infrastructure would also need to be ensured to support new technological demands (BIS, CPMI and MC, 2018). Auer and Böhme (2021) point out that a reliable technological infrastructure and relevant cybersecurity protections are significant elements to build trust in the new digital currencies. Additionally, international cooperation needs to take place to ensure interoperability and to develop a set of common protocols, which could be used to operate cross-borders payments. Whether CBDCs could ensure continuity of service after their launch, can only depend on the robustness of the technological solutions implemented and, on the possibility to adapt to the transactional volumes that will need to be processed. There are doubts on the technological readiness for CBDCs, as large-scale systems may not yet be technically ready, especially in the context of DLT. CBDCs may experience considerable technical and infrastructural problems, which could jeopardise the achievement of the planned benefits. While the envisioned elements of the CBDC architecture are discussed in the literature, the specific solutions envisaged are diverse and depend on different technological setups (e.g. distributed or centralised systems), the scalability of processing, the legal framework, the privacy aspects, and the requirement to interface the banking system infrastructure. Technical details remain unresolved, due to a lack of consensus but working on these details, with pilot projects and stakeholder collaboration, could help resolve the ongoing debate. The development of optimal solutions that balance speed, efficiency and security with privacy, demands continuous work across technological development as well as international coordination and partnerships between central banks, international organisations and fintech organisations.

2.2.11. INTEROPERABILITY WITH PAYMENT SYSTEMS

The ability of CBDCs to work with existing payment systems stands as a critical necessity for their successful implementation. The failure to integrate CBDCs with current financial systems makes them impractical to gain broad acceptance and operational functionality. System interoperability depends on design choices and standard protocol adoption, as these elements

determine the possibility to prevent fragmentation and support cross-borders transactions (BIS, 2023d; Kiff et al., 2020). The regulatory framework for cross-border interoperability encounters heterogeneous challenges, due to diverse legal systems, requirements for data storage and privacy protection rules. The use of divergent rules allows financial actors to operate with less stringent KYC/AML systems and capital controls. It may create possible regulatory arbitrage situations that can endanger CBDC policy goals and may generate market instability (BIS et al., 2024). The FSB and G20 Roadmap on cross-border payments aim to standardise the compliance procedures, reporting standards and supervisory requirements for cross borders payments (FSB, 2024a, BIS, 2023d). The OECD (2023) stated that organisations need to establish stable legal and governance systems to minimise their exposure to fraud, money laundering and terrorism financing risks. The technical implementation of interoperability faces difficulties, as CBDC systems operate through separate architectural frameworks, with diverse design choices. The validation and settlement processes of transactions operate differently under centralised systems, token-based systems and hybrid systems, according to the BIS et al. (2021a). The integration of these systems creates additional cybersecurity threats, because weaknesses in one network can spread to affect other connected networks (BIS and SNB, 2023). The ISO worked to standardise financial messaging through ISO20022 protocols, with digital identity systems and security protocols to support international data exchange. The DLT progress together with instant payment systems and regulatory technology solutions, may enable real-time compliance and scalable transaction monitoring, which improve security and operational efficiency. There is a consensus among researchers on the prominence of interoperability for CDDBs; however, there is no clear indications on the roadmap to achieve it or the technical standards to adopt. The key barriers to attain a standardised functional architecture include technical differences between systems, operational challenges and regulatory variances between countries. The implementation of successful CBDCs depends on extended cooperation between central banks, policymakers, industry players and international organisations. Multiple actors need to collaborate for the successful integration of CBDCs with domestic and international payment systems.

2.2.12. PROGRAMMABILITY

A major difference between digital currencies and cash is represented by the programmability, i.e. the capacity to embed settings in the code of a CBDC that automate transactions and/or enforce conditional rule(s), in presence of predetermined conditions. Smart contracts can self-execute agreements, when the conditions specified in the contract are met. The literature shows different views on this feature. Authors write that programmable CBDCs have the

potential to significantly strengthen inclusion in credit and financial markets. Peters and Panayi (2016) emphasise the potential benefits of programmable blockchain. Smart contracts can automatically execute rules for specific monetary policy transactions, such as stimulus payments, which may be subject to spending constraints, in terms of time, location, or specific categories of goods and services. Programmable smart contracts could transform the application of monetary policy rules, as they could enact new monetary policy instruments. These new capabilities for monetary policy could be compelling for central banks. DLT would be able to support programmability, however, central banks may need to address specific technological problems. Schär (2021) analyses smart contracts and DeFi in detail, as he argues that they may intensify the complexity of the design for security and privacy aspects. Consequently, if smart contracts are embedded, CBDCs might become more vulnerable to hacking than other transaction systems. Bulgakov et al. (2024) discuss issues of scalability and interoperability with other financial systems. With programmable CBDCs, it would be possible to design new functionalities to facilitate the implementation of monetary policies, and to enhance the payment efficiency. At the same time, the programmability adds complexity to the security, privacy and to the fundamental role of the banks.

C. SOCIO-ECONOMIC AND FINANCIAL INTEGRATION

The key determinants of the CBDCs' success are their ability to function within both the financial sector and the wider social and economic structure. The payment efficiency, financial inclusion and public trust of CBDCs depend on their adoption models, accessibility and distribution systems. The interoperability with cross-border payment systems brings operational advantages and transparency benefits, however, it may create difficulties for maintaining regulatory oversight, risk management and international coordination. This section examines the socio-economic and financial dimensions of CBDCs' implementation, focusing on distribution models, adoption and usage, accessibility, and international use in cross-border transactions.

2.2.13. DISTRIBUTION MODEL

The distribution model determines how CBDCs enter in circulation and function within the financial system, affecting operational costs, system stability and the organisational structure. Depending on the design choice made, distribution models may require substantial administrative support, to correctly channel CDBC and may depend on both appropriately trained personnel and dedicated technological infrastructure (Auer and Böhme, 2020). The

literature divides CBDCs into categories which include wholesale, retail and hybrid, based on the distribution methods.

Wholesale CBDCs are designed for financial institutions to execute interbank payments and securities transactions (WEF, 2021). Wholesale CBDCs restrict access to financial intermediaries, who operate wholesale payment and settlement systems (Auer and Böhme, 2020). The distribution model operates in a closed loop, whereby central banks provide digital tokens or balances to authorised intermediaries, who then utilise those tokens in payment systems and for securities settlements or interbank transfers. These systems can execute Delivery-vs-Payment (DvP) to improve clearing transactions in capital markets and Payment-vs-Payment (PvP) for foreign exchange transactions (BDF, BIS and SNB, 2021). Other areas are the tokenisation of securities, which integrates tokenised assets like stocks and bonds to make post-trade settlement more efficient (BIS and CPMI, 2019), and the liquidity management, enhancing the liquidity provision, and minimising counterparty risk. The Banque de France (2021) pointed out that wholesale CBDCs might have marginal direct impact for individuals. Wholesale CBDCs may ameliorate interbank processes but when implemented alone, they may not offer meaningful improvements for the overall public. In mature banking and financial systems, wholesale and retail CBDCs may be considered as complementary instruments that should be designed to operate concurrently and coherently across the various layers of the monetary system, to modernise payments.

Retail CBDC serves as a digital currency for public use by households and businesses, in commercial functions that mimic physical cash transactions (WEF, 2021). The CBDC distribution involves either a direct model (one-tier), where central banks handle end-user accounts and wallets and perform transactions; or an indirect model (two-tier), in which authorised financial intermediaries maintain CBDC accounts, while central banks focus on issuance and settlement functions (Auer and Böhme, 2020). In the two-tier model, vetted financial institutions handle customer onboarding and compliance processes, including KYC. Auer and Böhme (2020) discuss the two-tiered CBDC model that combines the intermediation principles and the traditional role of banks, limiting the possibility of disintermediating the banking system, but still enjoys the public mandate and several other benefits of CBDCs. The operational complexities associated with a two-tiered solution require active oversight of authorised intermediaries. The implementation of retail one-tier CBDCs could enhance financial inclusion, according to Boakye-Adjei et al. (2023), but central banks face the possibility of losing their role as people start to use central bank accounts for traditional banking services. Mitigating measures include caps on CBDC digital wallet holdings and transaction amounts, or tiered remuneration schemes (FSI, 2023).

Hybrid distribution models are also possible, when direct claims can be made on central banks, who manage issuance and record retail balances, while intermediaries handle transaction operations. Hybrid models integrate retail functions with wholesale payment systems. This design option may offer flexibility; however, it may also create operational complexity and coordination difficulties. Synthetic CBDCs may represent a variation of hybrid models, where private institutions issue stablecoins, fully backed by central bank reserves (Marthinsen and Gordon, 2024).

In actual implementations, the boundaries between CBDC models may blur, with central banks likely to adopt frameworks reflecting national priorities. Retail models may enhance accessibility; however, one-tier models may disrupt the financial stability and the banking intermediation principles. Hybrid models combine multiple approaches, but they may present governance challenges. Wholesale models improve settlement and cross-border system operations, yet their public reach remains limited only to specific market segments. CBDCs demands policymakers to balance operational efficiency with service accessibility, and to develop protective measures for disintermediation and financial stability. The main distribution models, along with their key features, advantages and risks are indicated in the table below.

TABLE 3: CBDCs' DISTRIBUTION MODELS

Distribution model	Features	Benefits	Risks and challenges
Wholesale	• Available only to eligible financial institutions and market operators. • Closed-loop settlement system. • DLT or centralised ledger technology.	• Enhances interbank settlement efficiency. • Supports DvP and PvP transactions. • Reduces counterparty and settlement risk.	• Limited direct impact for the public. • Requires harmonisation of industry standards. • Systemic risks may arise on current payment systems interfaced, depending on the design.
Retail	• Direct access for households and firms. • One-tier or two-tier distribution models. • Often on permissioned ledger.	• Broad accessibility and inclusion. • Cost reduction and improvement of transaction speed for payments and remittances. • Boost of monetary policy transmission.	• Bank disintermediation risks for one-tier models. • Complexity of the two-tier models. • Risks related to the cybersecurity of intermediaries.

Distribution model	Features	Benefits	Risks and challenges
Hybrid	- Combines retail access with wholesale settlement. - Shared roles between central banks and intermediaries. - May include synthetic CBDCs (i.e. stablecoins backed by central banks' reserves).	- Balances inclusion with efficiency. - Design adaptable to local requirements. - Encourages public-private cooperation.	- Operational and governance complexity. - Coordination issues with central banks and operators. - Generation of potential inefficiencies, without clear responsibilities.

Source: Author's elaboration.

2.2.14. ADOPTION AND USAGE

In the proposed framework, the investigation of adoption rate and usage of CBDCs, may be beneficial for considering the end users' perspective, and the actual phase of the implementation. Such reflections can guide decisions in both advanced and developing countries, albeit with varying motivations. Adoption rates can impact the achievement of the initial goals, set for the digital currencies. Improved payment performance and resilience, greater financial inclusion, and currency sovereignty might not be possible, unless CBDCs attain sufficient volumes of transactions and number of users in the issuing countries. There are multiple usage considerations that affect how quickly and effectively a CBDC may find its way into the public's consciousness and into the mainstream economy. Adoption and usage are tightly related to the other factors in the proposed model. For example, a clear regulatory framework establishes the scope and regulations of CBDC usage, including aspects such as data security, compliance to AML and CFT regulations, and interoperability with other payment systems (BIS et al., 2024).

Other researchers contend that CBDC might be undermined by the lack of regulations and guidelines, which would lead to users' mistrust (Bossu et al., 2020). According to researchers, privacy-friendly models including tiered CBDCs, which maintain anonymity for low-value transactions, might ease public concerns, while preserving existing regulatory standards (Murphy et al., 2024). Sound technological platforms are critical for CBDCs' operators and for usage and adoption (BIS et al., 2021a). For instance, Auer, Cornelli and Frost (2020) maintain that successful CBDC deployment and high usage rates depend on technology and regulation, on a conducive policy landscape and on early stakeholders' engagement. Likewise, distrust in

central bank policies might increase resistance in some countries. Through usage variables, Auer, Frost et al. (2021) found that CBDC adoption correlates with the level of digital payment infrastructure, and with the proportion of contactless and mobile payments in a country. These results indicate that governments and central banks should consider developing their digital infrastructure to support CDBC's adoption.

The academic literature points out that CBDCs cannot represent a universal remedy. As developed economies may focus on improving payment system efficiency and resilience, emerging economies may wish to prioritise financial inclusion. Researchers generally recognise that a defined regulatory regime and privacy protections are essential for the viability of these systems, since public confidence is crucial for the use of CBDCs (Carstens, 2023). CBDC adoption can be also used to support geopolitical purposes, for example, currency internationalisation (IMF, 2020). Digital currencies might disrupt international capital flows and may need global coordination and international standards-setting, a topic which is debated among academics and policymakers.

CBDCs' adoption and use may depend on the interplay of technology robustness, regulatory certainty, public trust and socio-economic factors. The adoption of CBDCs, across various jurisdictions, may be influenced by several factors such as trust, regulation, usability, and socio-economic context, rather than technology alone, as summarised in the table below.

TABLE 4: CBDCS' ADOPTION FACTORS

Adoption factors	Drivers	Barriers
Regulation and Governance	• Unambiguous legal framework. • Compliance with AML/CFT. • Status of legal tender.	• Lengthy and laborious development and approval of comprehensive regulation. • Inconsistent standards. • Risk of surveillance overreach.
Technology	• Scalable platforms. • Fast transaction speed. • Strong cybersecurity.	• Technical immaturity. • High infrastructure costs. • Stakeholders' support and collaboration required to interface CBDCs with existing payment systems.
Public Trust and Privacy	• Privacy and data confidentiality (via tiered identification and anonymity for low-value transactions). • Central bank credibility.	• Low trust in institutions. • Privacy concerns. • Fear of state monitoring.

Adoption factors	Drivers	Barriers
Usability and Financial Inclusion	• Access for unbanked and underbanked. • Simple and inclusive user interfaces.	• Digital divide across population. • Limited financial and digital literacy. • Exclusionary KYC requirements.
Socio-Economic and Political Context	• Support for payment resilience. • Currency sovereignty. • Potential for internationalisation.	• Risk of bank disintermediation. • Uneven digital infrastructure. • Geopolitical ambitions.

Source: Author's elaboration

2.2.15. ACCESSIBILITY

Accessibility shapes how widely and reliably a CBDC can be distributed and can function across a variety of devices, both online and offline. The success of CBDCs requires them to deliver reliable financial services to all users for their daily needs. The BIS et al. (2020) indicated the CBDCs could only develop into a valid alternative to cash, if they will become extensively available. The accessibility provision allows all population segments to use systems which operate, regardless of infrastructure constraints (WEF, 2023).

Online-only CBDCs provide businesses and individuals with the ability to make borderless payments, reducing payment obstacles. Advocates of online-only CBDCs highlight the possibility to utilise existing infrastructures as an additional point of emphasis. Online-only CBDCs may interoperate with current payment systems and may be able to enhance the efficiency of payments, by processing transactions almost in real-time, and by integrating into online services and optimising transactional costs (Chu et al., 2022). Conversely, the lack of reliable connections, can represent a significant limitation for those living in areas not served by sufficient telecommunication systems. The current payment systems work better with online-only CBDCs, but these applications create challenges for people who do not have digital access and for specific geographic areas. Online-only CBDCs face cyber threats that result in operational risks as well as privacy rights restrictions. The decision to prioritise online-only CBDCs, due to their efficiency in development and implementation, is controversial, when considering the digital deprivation in many areas of emerging economies.

Offline CBDCs are functional without internet connectivity and may enable transactional capability for larger shares of population, including the people who are at the margins of the

financial system, the unbanked and underbanked individuals (Minwalla et al., 2023). Advocates of offline CBDCs argue that offline provision of central bank money at the point of sale could prevent transactional failure (Chu et al., 2022). Offline CBDCs have broader applicability during major disasters such as natural hazards, armed conflicts, or financial crisis. Offline CBDCs may also be perceived as more resilient, especially in scenarios of widespread outages, operational breakdowns, or attacks perpetrated by hackers. Effective offline CBDC may require an upgrade of existing payment infrastructures and may necessitate new settlement systems, with backup nodes to maintain safety, even when internet fails (Chu et al., 2022). However, currently there is not enough evidence to suggest that offline technologies can be implemented widely or securely. It is worth noting that offline CBDCs are accommodative, amplifying the number of possibilities for users, but the risks of prosecuting this pathway remain significant. To aptly replace the functions of cash, including providing privacy, CBDCs must attempt to offer analogous functionalities, i.e. private, anonymous transactions with no tracking. The offline functionality provides the anonymity and sense of finality of cash payments. Researchers encourage technological innovations that allow for private, anonymous, and final transactions both online and offline. Minwalla et al. (2023) highlight offline CBDCs as inclusive and resilient systems, yet experts continue to be concerned by potential risks of fraud, double-spending, and permanent payment loss, due to the absence of real-time verification. Moreover, the ability to use a CBDC offline might undermine transactions' compliance. Chu et al. (2022) highlight the technical difficulties of making payment systems more secure. Solutions proposed include ensuring the use of secure, dedicated hardware devices, and the latest cryptography methods, which may imply an increase in costs and complexity.

Researchers have suggested a combination of online and offline functionalities that would provide offline capabilities for small-value payments, while large-value payments would still have to be performed online. Offline accessibility may deliver superior system reliability and inclusivity; however, it might create major technical and security obstacles that organisations might struggle to overcome, due to the complex nature and high implementation expenses. The deployment of these systems would encounter major challenges which may prevent their widespread use. Conversely, online-only CBDCs are more efficient but do not necessarily enable central banks to meet their goals of universal access and financial inclusion. A CBDC that is accessible only online may not meet the favour of the overall public. Striking the right balance between online and offline accessibility in CBDC design is therefore an important and potentially delicate issue. The literature illustrates the different types of trade-offs that need to be carefully considered by central banks, when devising the design features of CBDCs. Future research into suitable technological solutions for offline CBDC problems may support the

possibility to develop hybrid CBDC systems to maximise the benefits of both online and offline functionality.

2.2.16. INTERNATIONAL USE FOR CROSS-BORDER TRANSACTIONS

To cater for several users' requirements, CBDCs need to be able to interoperate with existing digital payment systems, both domestically (for instance, with Real-Time Gross Settlement systems or RTGS) and at international level (e.g. through the BIS mBridge platform services). This is important for ensuring that CBDCs can be used alongside other forms of banking services, payment systems and cross-border financial networks (BIS, CPMI and MC, 2018). The establishment of CBDC digital wallets may allow individuals and businesses to execute transactions. To implement interoperability, central banks must work, alongside private financial institutions and payment service providers, with international organisations to create common standards and technical protocols to bridge private and public digital payment systems (WEF, 2023). This issue becomes critical for international payments since varying regulations are employed across several nations. For instance, many national payment systems adopted standards such as the ISO-20022 protocol, however others, like the Federal Reserve Bank Fedwire Funds service, an RTGS system in the USA, transitioned to the ISO20022 message format only in July 2025 (Federal Reserve Banks, 2025). Differences in the standards adopted may lead to lack of interoperability for cross-border payments. Resolving this challenge will involve significant technical coordination and standards' setting, often with the support of international organisations. CBDCs could bring significant changes to the international payment infrastructure and to the wider financial system (BIS et al., 2020). The debate in the academic literature reveals a complex and diverse range of positions between potential efficiency gains in cross-border transactions and financial stability and monetary sovereignty risks for jurisdictions. Cœuré (2018) and the IMF (2024b) emphasise potential operational efficiency gains and improved payment infrastructures, while other researchers, such as Brunnermeier, James and Landau (2019) and the WEF (2023) point to geopolitical and economic risks associated with the international adoption of CBDCs. The BIS et al. (2020) note that cross-border payment systems may be slow and costly, while using a direct central bank payment channel may improve efficiency, by reducing reliance on extensive multi-tiered correspondent banking networks. Mu (2024) analyses China's CBDC pilot, which involved processing millions of transactions and encouraging domestic merchants to adopt the technology, seemingly providing strong support for a highly usable and large scale CBDC. While modern technology can enable the innovation, its proper deployment depends on an several economic, legal, and geopolitical elements. Adrian, Mancini-Griffoli and Zettelmeyer (2021) examine the CBDCs' elements and how they may influence the global payments and

currency substitution. The points raised about the international implications of the CBDCs' ecosystem highlight the necessity to ensure a collaborative approach in the development process and rollout. Independent actions by major economies could have global implications for financial stability and they may prevent the full realisation of the expected benefits.

Interoperability can play a crucial role, a CBDC system in a specific country could interact with other national CBDC systems and execute international payments. The digital nature of CBDCs calls for international coordination and cohesion in guiding principles. Bossu et al. (2020) attempts to understand the challenges of developing a common regulatory regime and focuses on differences of legal frameworks. International organisations could lead the way in creating common standards. Carstens (2021) argue that international cooperation is required to create common technical standards and legal frameworks. Even the design of CBDCs may depend on these broader contextual issues of coordination. Auer, Haene and Holder (2021) favour the implementation of multi-CBDC arrangements for the execution of global payments transactions.

D. SUSTAINABILITY AND INCLUSIVITY

A more responsible attitude of policymakers and groups of the population, and the attention of central banks to environmental, social and governance issues, introduced themes such as financial inclusion, environmental sustainability and social equality, among CBDCs' objectives. Central banks and policymakers may evaluate their capacity to decrease digital inequality and to assist disadvantaged populations, while maintaining economic fairness and environmental protection. The literature shows that CBDCs may improve inclusivity and resilience, but there are concerns about possible unequal access, surveillance and environmental costs, that may be due to poor design choices.

2.2.17. *PRIVACY*

The protection of individual privacy rights, while upholding the legal requirements to monitor and oppose criminal activities is one of the most delicate trade-offs to balance. Digital currencies necessitate simple interfaces and privacy protection, in compliance with AML and CFT regulations. The public acceptance of the system depends on the privacy features design, as users tend to avoid systems with tracking capabilities that are too invasive; however, complete anonymity would lead to legal and compliance issues. A central line of academic debate contrasts anonymity as a right, with traceability as a safeguard. The protection of

personal financial data and the prevention of unauthorised monitoring represent the key reasons for anonymity advocates. Ballaschk and Paulick (2021) explain that users need anonymity to protect against excessive government surveillance. Privacy-preserving CBDCs that offer transaction secrecy, like traditional cash may experience high adoption rates. From this perspective, anonymity could also foster financial inclusion and reproduce the role of cash in retail payments. The use of anonymity has raised concerns among opponents, who fear it will enable illegal activities. State-backed CBDCs must follow AML and CFT regulations, according to Murphy et al. (2024). Niroula et al. (2024) warn that unregulated capital movements may be facilitated by anonymous capital flows. In this scenario, enabling anonymity for some payments and identity controls for large transactions could offer a more balanced approach.

A tiered privacy model which requires identification for large transactions but allows anonymity for small transactions has been suggested as a possible solution, according to Darbha and Arora (2020). DLT may achieve improved transparency and compliance through its capability to create permanent records and embed programmable smart contracts (Peters and Panayi, 2016), though scalability and interoperability challenges remain (Houben and Snyers, 2018). There are examples of potential middle-ground approaches, including token-based CBDCs, which might favour the users (Chaum, Grothoff and Moser, 2021), and account-based systems, which may disappoint individuals, merchants, and payment providers, but may offer regulators ease of monitoring and compliance (Ballaschk et al., 2021). The trade-off about privacy is exemplified by the tensions between personal freedoms and regulatory control. The implementation of excessive transparency creates risks for surveillance, public distrust and resistance to adoption (Murphy et al., 2024). Financial operations that lack identification methods pose major risks to both legal and financial monitoring systems. The ECB (2020) recognised this challenge, when stated that the digital euro would protect user privacy, while preventing illegal activities. Research shows that the level of public trust in privacy features may determine the success of CBDCs. User privacy protection systems need to achieve the right equilibrium between privacy measures and regulatory compliance, to gain lasting acceptance from users.

2.2.18. INCLUSIVITY

People need financial services access to meet their fundamental requirements and participate in economic activities. The literature presents CBDCs as financial inclusion tool, which provide secure efficient accessible services to unbanked and underbanked populations (Bossone, 2022). The financial sector has made progress toward expanding access to financial services,

yet major disparities continue to exist mainly in developing nations and disadvantaged social groups. The implementation of CBDCs may reduce financial barriers but requires proper design to eliminate structural impediments that may prevent financial inclusion. Research studies maintain a neutral stance about CBDCs, as they could promote financial inclusion, yet they might also create barriers to access. It is important to note that, since CBDC primarily represents cash in digital form, additional features to support financial inclusion may be developed by financial intermediaries, to facilitate access to saving, investment and/or credit products.

The implementation of CBDCs may bring several advantages which include lower transaction expenses, direct access to digital wallet funds, and financial services for unbanked populations. Offline functionalities and device-agnostic access features enable broader accessibility and improving inclusion (Auer et al., 2022). Evidence from mobile money adoption suggests that digital payment innovations may improve access, when combined with enabling regulation and supporting infrastructure (Ozili and Náñez, 2024). The Sand Dollar in the Bahamas serves as an actual case which demonstrates how CBDCs enhance financial services delivery to residents of distant locations (CBOB, 2019). Technological gaps, limited smartphone availability, scarce digital and financial skills, along with restricted internet access may represent important barriers for specific groups of population (Niroula et al., 2024).

In specific cases, CBDCs might exacerbate financial exclusion, as those unable to meet requirements or impacted by low financial and digital literacy could remain excluded (WEF, 2023). The combination of insufficient security measures with unsatisfactory privacy protection might worsen current social gaps (Mancini-Griffoli et al., 2018). The adoption of CBDCs does not ensure that all population groups may automatically receive access to them. Financial inclusion success depends on three essential elements which include improving digital and financial literacy, building institutional trust and creating regulatory frameworks that simplify operations and protect consumers. According to Auer et al. (2022) and Boakye-Adjei et al. (2023), user-friendly interfaces, offline access and interoperability with current payment systems may increase accessibility. CBDCs should not be viewed as a single technological answer to solve all problems.

The implementation of CBDCs in developed countries may support the reduction of existing financial obstacles, which prevent disadvantaged populations from accessing banking services. In emerging economies, people may use CBDCs to replace expensive or unreliable services. Central Banks should avoid the increase of the digital divide, protecting users from new system vulnerabilities.

2.2.19. ENVIRONMENTAL IMPACT AND SUSTAINABILITY

The environmental implications of CBDCs are subject to specific attention by central banks and policymakers. Central banks need to identify strategies to reduce the environmental effects of digital currencies. The deployment of CBDCs requires powerful computing resources, together with secure systems, although these solutions may consume less power than cryptocurrency networks. The implementation of energy-efficient systems has become a priority to achieve sustainability goals. CBDCs have the potential to reduce environmental and financial costs of physical cash. The process of managing cash requires significant resources, as it involves producing and distributing currency, maintaining storage facilities, ensuring security measures and performing the periodic replacement of worn-out banknotes and coins.

The production of banknotes and coins, along with anti-counterfeiting technology implementation, money transportation security and cash stock management generate considerable expenses (Khiaonarong and Humphrey, 2019). Additional costs include staffing for protection against theft and counterfeit, and frequent replacement cycles (Bergman et al., 2007; Chakravorti et al., 2013). These costs scale with the reliance on physical cash. The transition of economies toward digital payment systems has made CBDCs more attractive, as a digital payment solution which could reduce transaction costs, while offering a secure public payment system.

Researchers highlight that CBDCs could deliver environmental and efficiency gains. Bordo and Levin (2017) believe that CBDCs may function as a better payment system, eventually reducing the need for physical money. Khiaonarong and Humphrey (2019) suggest that CBDCs may decrease banking service fees, lower cash management costs and reduce its impact. Similarly, Mancini-Griffoli et al. (2018) and Khiaonarong and Humphrey (2019) support the idea that CBDCs may reduce the requirement for physical money production, distribution and storage, reducing consumptions. Higher adoption rates would amplify these effects, by reducing the residual costs of cash still in circulation, whereas low adoption would limit the benefits.

The technological design may impact the energy requirements, carbon emissions and overall sustainability of CBDCs (Paradigm Research, 2024). Key performance indicators to facilitate the tracking of the energy consumption may include the annual CO₂ emissions of CBDCs' systems, the amount of energy consumed per transaction, and the CO₂ equivalent emission for transaction. Researchers warn that CBDC systems require significant technological and operational resources which could reduce some of the advantages of digital currency. Auer

and Böhme (2020) indicates that the required infrastructure development for system maintenance, cybersecurity protection, backup systems and volume capacity expansion requires significant investment. These expenses may decrease some of the environmental advantages that result from producing and circulating fewer physical banknotes.

The sustainability equilibrium depends on effective digital infrastructure maintenance and on development plans. The implementation of CBDCs allows payment systems to incorporate sustainability goals into their operations. Through programmability central banks can establish green incentives, by lowering fees for sustainable transactions and rules to encourage environmentally beneficial consumption and investment. The system enables financial transactions to fund climate and sustainability goals, which could enable CBDCs to function as active green finance facilitators instead of neutral payment instruments.

The benefits of these technologies depend on their adoption rates, on effective system design, and on proper oversight. The next table presents a comparison between environmental and cost impacts of the cash usage and CBDCs.

TABLE 5: ENVIRONMENTAL AND COST IMPACTS OF PHYSICAL CASH VERSUS CBDCs

Aspect	Physical Cash	CBDCs
Production and circulation	High expenses for materials and energy needed for printing, minting and implementing anti-counterfeiting measures.	The digital nature of cryptocurrency allows for minimal production expenses due to technological infrastructure.
Distribution and storage	Transportation services, protection measures and periodic replacement with high-cost impact.	Cloud or on-premises infrastructure, licencing and maintenance services, security patching, periodical upgrades represent most costs
Operational risks	Subject to theft, forgery, wear and tear, and expensive logistics and security measures.	Introduce new operational risks such as cyber threats; requires constant monitoring and compliance to several regulations.
Environmental carbon footprint	Production of banknotes, minting of coins, periodical inspection and replacement, waste management of destroyed banknotes and coins.	Energy usage of datacentre, merchant and end user devices. The overall environmental effects of digital currencies remain uncertain as they depend on the efficiency of the infrastructure.

Aspect	Physical Cash	CBDCs
Scalability of costs	Costs increase with cash demand and circulation.	Costs linked to transaction volume, scaling, and system resilience.
Incentives for green finance	None.	Programmability can embed sustainability goals (e.g. fee reduction for green transactions).

Source: Author's elaboration.

2.3. IMPLEMENTATION TIMELINE FOR CBDCs

The development of a CBDC needs a strategic approach that includes design and planning phases, followed by regulatory changes, technological deployments, and public involvement. The potential duration of the implementation timelines for CBDCs depends on the unique combination of regulatory frameworks, technological readiness and policy objectives that exist between different countries. Four critical stages govern the implementation timeline.

a) Preliminary research (12-24 months)

The first step for central banks involves conducting feasibility studies, to determine reasons behind the decision, evaluate effects and select basic design elements (Auer, Cornelli and Frost, 2020). The objectives could focus on improving financial inclusion, enhancing payment efficiency and ensuring monetary sovereignty. The evaluation of design choices occurs during this stage, and it may assess alternatives such as DLT token-based or centralised account-based systems, different solutions between retail, wholesale and hybrid systems, and may require wide participation from central banks, policymakers, and academic experts. This phase may be completed in 12 - 24 months, however it can last more, in case of indecisiveness to proceed to the next phases.

b) Regulatory frameworks (24-36 months)

The updates in the legislation should focus on domains such as compliance with AML/CFT regulations and privacy, data protection standards (Murphy et al. 2024). In addition to appropriate laws, the protection of consumers and privacy need suitable governance structures (Ballaschk and Paulick, 2021). The process requires authorities to work together during this stage, which extends for two or more years.

c) System architecture and pilot testing (36 months)

The process of establishing legal and regulatory frameworks may direct the selection of the system architecture (BIS et al., 2021a). The development and implementation of technological solutions must include feedback loops from the stakeholders, to enable prompt design adjustments and bugs' correction. The testing phase should foresee pilot projects, for the evaluation of different system functionalities and user acceptance with small groups of participants (WEF, 2021). This phase may last up to three years.

d) National rollout (24 months)

The last stage of implementation occurs after the completion of pilot projects, to enhance user adoption, to connect CBDCs with existing payment systems and to launch public awareness campaigns (IMF, 2024b). National monetary authorities should monitor the system performance, together with adoption rates and macroeconomic effects, to determine suitable policy changes to maintain financial stability, according to the BIS et al. (2021b). This phase may take up to two years.

e) Overall timeframe

The entire process from research to widespread implementation may require four to ten years to complete, depending on legal preparedness, technological readiness and policy targets. The BIS (2023d) states that jurisdictional regulations, design choices and project complexity represent the key drivers for the implementation. Wholesale CBDCs may exhibit a faster deployment timeline compared to retail CBDCs, in consideration of the time required for retail CBDCs to evaluate and approve adequate legal frameworks, conduct information and awareness campaigns and, most importantly, gain public trust (BIS, CPMI and MC, 2018). The timelines may be influenced by the level of digital literacy of the population.

2.4. CONCLUSIONS, POLICY RECOMMENDATIONS AND FUTURE RESEARCH AGENDA

CBDCs constitute an innovation for monetary and financial systems. CBDCs offer a public option to the privately issued digital currencies (such as cryptocurrencies and stablecoins) and central banks should focus on creating CBDC systems that can complement and not replace the cash circulation. The implications encompass the whole paradigm of money issuance, transfer, and use, carrying a plethora of opportunities across diverse dimensions, improving the efficiency and security of the payment systems, integrating with domestic and cross-border payment infrastructure, to execute transactions with immediate settlement; reducing the fragmentation of liquidity; potentially lowering the costs of intermediation; improving the financial inclusion; and strengthening the effectiveness of monetary policy tools, giving the possibility to implement monetary policy interventions in a more precise manner. The proposed framework for classifying CBDCs, as identified in chapter 2.1, consolidates various relevant factors into four coherent thematic dimensions, and it may become a meaningful tool for central banks and policymakers to evaluate the different aspects of CBDCs' implementation and to consider the potential design choices.

Central banks need to consider political and ethical factors, along with technical and economic aspects, during the development of CBDCs. The successful implementation of CBDCs depends on their system design and on the establishment of flexible legal frameworks and international agreements. CBDCs require a careful, evidence-based and inclusive approach, and demand newly developed regulatory frameworks, to maintain effective interoperability with existing banking and payment systems. Legal and regulatory frameworks need to be adapted to national requirements. Regulatory arbitrage may become an undesired practice and undermine the interaction between different jurisdictions, forcing policymakers to collaborate to maintain interoperability. Central banks should cooperate with international institutions for the design choices and for feasibility studies and may consider launching public consultations on the design of the user experience, enhancing the usability of their digital wallets. Efforts should be focused to the implementation of resilient solutions, considering the local technical and budgetary constraints. The digital wallets should embed the latest security features, to achieve public trust. Central banks should assure a satisfactory transaction execution speed to perform real-time exchanges. In designing the optimal systems, central banks should evaluate the trade-offs between scalability, security, and user experience requirements, as they would entail compromises in the technical solutions adopted. In this sense, it is mandatory to ponder accessibility requirements and infrastructure cost. The adoption of energy-efficient solutions would enable the achievement of sustainability objectives, without compromising on operational efficiency. The interoperability with domestic

payment systems, other digital money platforms, and the integration with international payment systems may ensure that CBDCs would not remain in silos and would eventually encourage the adoption rates.

At geopolitical level, CBDCs could play an important role in relation to the international monetary order. CBDCs may create new opportunities for international financial collaboration. Central banks should coordinate to enable CBDCs to integrate with existing global payment infrastructure and to meet established international regulatory requirements. The appropriate governance models must be chosen to manage domestic and cross-border interoperability of CBDCs, for promoting financial stability and for encouraging economic growth. CBDCs may impact international trade and diplomatic relationships. The international adoption of a specific CBDC for foreign payment transactions might weaken the status of existing reserve currencies that support the global trade system. Major CBDC issuers could influence the development of future global financial infrastructure, especially in countries with large unbanked or underbanked populations. The international use of digital currencies, issued by foreign governments, could hinder the sovereign control of third countries over their monetary policy. Privacy and data protection considerations should be analysed from the early design stages and clearly presented to all stakeholders. The establishment of optimal data governance structures may support the avoidance of potential abuses in data access. As CBDCs can be fully traceable, safeguards may be required to inhibit authorities from scrutinising individuals' spending habits in a granular manner. Balancing individual privacy rights with the adherence to AML and CFT regulations, may support the adoption of digital currencies among the population.

The programmability of CBDCs may pave the way to the operationalisation of smart money, which can enforce policy conditions, such as time-limited currency (currency that can expire automatically, if it is not spent within a specified time), or targeted stimulus (money that can be programmed to be spent only in designated sectors, goods and services, or in determined geographic areas). CBDCs could also be programmed to incentivise environmental objectives. For instance, by offering lower transaction costs for green investments, or by embedding carbon-tracking features into the new digital currency systems. Beyond the pragmatic benefits that could be achieved in the payments area, CBDCs could alter monetary and fiscal policies, especially if there might be a direct drive from governments to deploy direct fiscal interventions through CBDCs, to provide stimulus payments or to fund public works.

There are also challenges, which include the redrawing of the boundaries between the responsibilities of monetary authorities and traditional banks, in terms of cybersecurity, privacy,

central bank independence and financial stability. The digital nature of CBDCs may introduce a new class of operational risks, with new cybersecurity threats. The implementation of new technology demands comprehensive risk assessments. Significant tools to assist in this process may be an analytical design, based on standards developed by international organisations, the analysis of early feedback from users through pilot projects, the engagement of a wide range of stakeholders, and the continuous monitoring of the impacts of CBDCs in the financial systems, with the possibility to adjust project targets, to embed the insights gained during the project. Considering that CBDC are state-backed currencies, financial inclusion targets should be carefully considered, to take advantage of the new technologies to improve the conditions of the overall population. CBDCs may enable financial inclusion in areas and in groups of people currently precluded from traditional banking coverage. Central banks and governments may implement the necessary digital infrastructure in rural or remote areas. Simplified user interfaces and digital wallets may integrate with existing mobile banking platforms and facilitate the accessibility for individuals with low levels of technological literacy.

With CBDCs implemented across only few countries, researchers lack data on the effects of CBDCs on regulatory compliance and financial stability over the long term. Understanding and measuring CBDCs would be key in ensuring financial stability. Policymakers should consider a balance between strict regulations and innovation targets, to implement a solution that can cater for the specific needs of the issuing country. The prioritisation of financial stability becomes paramount, to avoid risks of disintermediation and, ultimately, to enable the achievement of most of the objectives. The definition of the interest remuneration policies clarifies the central bank strategy towards CBDCs. Monetary policy effectiveness might generate disintermediation risks. Central banks risk competing with retail deposits, when implementing in CBDCs, a mechanism to transmit monetary policy targets, incentivising savings with positive interest rates or inducing residents to increase spending through negative rates. Conversely, central banks can adopt a more neutral approach, by setting a no remuneration policy, which conform CBDCs to cash, thereby renouncing to the application of interest rates, that can be perceived as invasive. To prevent disintermediation risks, central banks may also decide to set CBDCs' holding limits, or transactional caps for both individuals and businesses, thus setting a limit to the potential deposit withdrawals, and therefore reducing funding requirement risks for traditional banks.

The implementation of pilot projects is recommended to perform trials prior to the official launch, during which, valuable information can be gathered to fine-tune the implementation and to tailor it to the specific groups of the population, gathering public feedback also on the

best possible approach. The deployment plans need to evaluate factors like the population's age distribution as well as their proficiency with digital tools, and available internet access across the country. To optimise adoption rates and to reduce launch risks, staged releases are recommended. By promoting the distribution and usage through traditional banks, merchants, and payment providers, central banks can leverage the existing banking infrastructure, ensure the implementation of effective KYC and regulatory practices and expand the customer care support to individuals, which can be specifically advantageous during the initial launch. The organisation of awareness campaigns, through multimedia supports, personalised for the specific demographic characteristics of the population, would ensure usability and gain user confidence.

During all phases, central banks should gather continuous feedback from stakeholders, to ensure that corrective actions could be enacted on time and to be able to reconcile national priorities, with international interoperability and geopolitical ambitions. Relevant research questions could narrow the gaps in the current literature and investigate, through comparative studies, the implementation of the different CBDCs design choices, in the countries where they were launched, observing how the new technologies are being utilised, which factors can be considered as key drivers of CBDC acceptance and how individuals and companies are adopting them. Other open study areas are related to the creation of protocols for the interoperability of CBDCs with domestic and international payment systems, to the settlement of tokenised assets through CBDCs, to the creation of standardised regulatory frameworks that central banks and policymakers may adopt to ensure a successful deployment, and to the ascertainment of the environmental impact of CBDCs, to ensure their sustainability.

The CBDC ecosystem requires further research and international cooperation to realise its full potential. Future research may focus on the necessary technology solutions, to scale, to embed privacy protection, while advancing inclusiveness and sustainability, and on the behavioural adaptations for people and businesses, together with the legal frameworks needed to support CBDCs' successful implementation. National monetary authorities, policymakers and all the stakeholders involved should collaborate to identify a balanced equilibrium, between financial innovation, privacy protection, supervisory requirements, and financial inclusion, with the aim to ensure the successful enactment of CBDCs.

2.4.1. POLICY RECOMMENDATIONS

The following recommendations may be considered by national monetary authorities, policymakers, technology providers and international stakeholders to assess CBDCs and to enhance their implementation process:

1. Strengthen the regulatory frameworks.
 - The establishment of clear rules should outline key areas such as the CBDCs' distribution methods, data protection measures, AML/CFT compliance requirements and consumer protection standards.
 - The achievement of legal certainty and the alignment of domestic law with international standards, to prevent regulatory arbitrage opportunities represent important concerns for policymakers.
2. Prioritise financial stability.
 - The design of CBDCs should function as an addition to existing commercial banking operations, rather than seeking to replace them.
 - The following measures may help prevent bank disintermediation: digital wallet holding limits, no-interest or tiered remuneration, and transaction caps.
3. Balance privacy with compliance.
 - CBDC systems should protect personal information of users, while maintaining the ability to track transactions classified as high risk.
 - Researchers should investigate advanced privacy solutions, including tiered anonymity systems and privacy-preserving cryptography methods.
4. Promote financial inclusion.
 - The implementation of accessible systems, with user-friendly digital wallets that integrate with low-tech devices and function offline without internet access, may support the adoption rates.
 - The promotion of awareness initiatives such as digital and financial literacy campaigns, may strengthen the results of investments in technical solutions and in digital infrastructure.
5. Implement resilient technology.
 - Central Banks needs to develop or invest in infrastructure systems, capable to scale their capacity according to transactional demands, while enhancing security levels and protecting against cyber threats.
 - The implementation of hybrid technological systems may unite centralised resilience capabilities, with specific decentralised elements to accelerate execution at user level.

6. Promote sustainability.
 - The deployment of energy-efficient technologies may reduce the carbon footprint and decrease the environmental effects of CBDCs.
 - The development of programmable features may be used to motivate users to adopt green finance and carbon-neutral solutions.
7. Foster interoperability and international cooperation.
 - CBDCs should be integrated with existing systems, and the broader payment services ecosystem, to prevent the creation of silos and the fragmentation of liquidity pools.
 - The BIS, IMF, FSB, WEF, World Bank and other international bodies, may support the coordination efforts required to establish common standards for international interoperability.
8. Plan for a phased and adaptive implementation approach.
 - Soft launch the platform and services through dedicated pilot projects and phased rollouts, testing in small scale the adoption, scalability, and public trust.
 - Gather feedback from users and stakeholders, to implement required adjustments.

2.4.2. FUTURE RESEARCH AGENDA

The development of CBDCs made substantial progress over the last years, however key areas need additional focus. Researchers may fill current knowledge gaps through future studies, across the four dimensions of the proposed framework.

A. Policy, Regulatory, and Governance

The evaluation of CBDCs requires the study of the long-term effects on financial stability, economic growth, and on disintermediation implications. Significant areas of analysis may regard the implications of national geopolitical ambitions in the design and implementation of CBDCs, the potential risks of digital dollarisation and the consequences on monetary sovereignty.

B. Design and Technology

The evaluation of various CBDC architectures requires comparative studies to assess hybrid solutions, which combine centralised features with innovative decentralised elements. Researchers may study the creation of interoperability standards and support cross-border pilot projects, to achieve technical integration and to secure international payment settlements.

C. Socio-Economic and Financial Integration

The combination of CBDCs with other digital currencies, electronic money and digital assets, should be further explored, in consideration of developing countries, where mobile money represents a key instrument for financial inclusion. The usage of CBDCs might be challenged by existing solutions, developed by private firms. The assessment of these entry barriers may be crucial for increasing the adoption rate and the transactional usage of CBDCs.

D. Sustainability and Inclusivity

Research groups should evaluate the environmental impacts of digital currencies, while exploring their programmable features and design elements, for the achievement of sustainability objectives. The evaluation process should assess energy efficiency, while studying the potential of CBDCs for supporting green financial programs.

CBDCs may bring more than technological progress, representing a structural transformation in the nature of money. By addressing the current gaps in the research, through comparative and interdisciplinary studies, central banks and authorities, seeking to design effective, sustainable and trusted digital currencies, may be sustained in the achievement of important objectives for the society.

CHAPTER 3. COMPARATIVE STUDY OF PRIMARY CENTRAL BANK DIGITAL CURRENCIES

National monetary authorities began issuing CBDCs to support traditional fiat money during the past years. Three CBDCs were launched as of 23 October 2025, i.e. the Sand Dollar from the Central Bank of the Bahamas (CBOB), the eNaira by the Central Bank of Nigeria (CBN), and the Jamaican Digital Exchange in Jamaica (Atlantic Council, 2025). Among the CBDCs in pilot phase, there is the e-CNY, issued by the People's Bank of China (PBoC). The e-CNY represents an advanced CBDC among major economies, with 180 million users and over 7 trillion-yuan transactions processed by July 2024 (Mu, 2024). This study investigates the design choices, implementation processes and governance structures of three CBDCs' initiatives, including the Sand Dollar in the Bahamas, which was the first issued CBDC in the world, the eNaira in Nigeria, the first CBDC issued in Africa, and the e-CNY currently piloted in China. The paper analysed and compared three different CBDC implementations, among the first in the world, covering distinctive geographies, across different types of economies, diverse groups of population, and various technological and operational approaches. By reviewing three primary use cases, this paper seeks to explain how the specific design decisions (such as monetary policy goals, legal frameworks and technological solutions) may be influenced by the broader economic, political, and technological contexts of each country, exploring how CBDCs may align with national strategies, such as financial inclusion, modernisation, geopolitical objectives, or financial stability. The analysis demonstrates that an innovation in digital currencies can cater for a combination of several objectives, and it provides important lessons learned for policymakers and national authorities considering the adoption of CBDCs in their jurisdictions, to understand context-based implementation approaches and the required stakeholders' engagement.

The case studies were identified to demonstrate the impact of CBDCs across different scenarios, i.e. in small, medium and large economies, with a population polarised between cities and rural areas or scattered across remote islands or with an international diaspora, over centralised and decentralised technical solutions, to ascertain where the intrinsic value of digital currencies could emerge and be observed. In the selection of case studies, there is a representation of diverse adoption and usage levels, and different technological solutions from simple to advanced, using DLT and centralised systems, with online and offline capability and varying degrees of programmability. The case studies also present a balance between individual privacy rights, with multi-tiered KYC approaches that enable anonymity, and strict compliance to the regulations.

The implementation of the Sand Dollar can illustrate the impact of CBDCs in small economies, with a distributed population, a potential to grow regionally (in the Caribbean Community), a two-tier distribution model, a simple technological solution using permissioned DLT with low-level of programmability, and a balanced approach between privacy and regulations. The eNaira can prove the impact of CBDCs in medium economies, with population composed by residents and overseas emigrants interested in cross-border remittances, a two-tier distribution model, an intermediate technological solution using the permissioned Hyperledger Fabric platform, with support for programmability, and a multi-tiered KYC approach that enables anonymity. The e-CNY can demonstrate the impact of CBDCs in large economies, with vast population, polarised across cities and rural areas, large processing volumes and pilot projects ongoing for cross-border usage in Hong Kong. It has a two-tier distribution model, a custom technological solution using a mostly centralised platform, with advanced programmability, and a dual offline wallet system, ensuring enforcement of regulatory compliance.

The purpose of this paper is to deliver an analytical comparison of diverse CBDCs' design choices, applying the comprehensive framework outlined in chapter 2, with the intention of identifying the strengths and weaknesses of the different applications. and to gain valuable lessons learned. The author acknowledges that there are limited studies which fulfil similar research objectives on these CBDCs. Readers can gain a conceptual understanding of the three selected CBDCs, their key components, and an analysis of what part CBDCs can play to achieve the stated objectives, across all the variables identified in the framework. The papers relevant for the research, were chosen among those available from primary literature from academic researchers, based on the journals' ranking in the Academic Journal Guide (Chartered Association of Business Schools, 2024), and papers from international institutions (BIS, IMF, FSB, OECD, WB, WEF, etc.), national monetary authorities working in the field, and from the central banks who developed, released and managed the three CBDCs, thus providing updated information, valuable for contextualising the development areas and demonstrating current tendencies.

This study is impacted by specific limitations, namely the research focuses on the comparison of launched CBDCs through a framework, created by the author in chapter 2, that could support researchers in analysing and better understanding CBDCs, however, considering the novelty of the field, new changes happen on a frequent basis, and they may have an impact on the conclusions reached by this research. Since the subject of the study is actively being explored by different actors, researchers, policymakers, monetary authorities and international organisations, new events impacting CBDCs occur frequently, with developments that might

have drastic impacts on digital currencies, e.g. the Executive Order issued by the White House on 23 January 2025, which halted the establishment of CBDCs in the USA (The White House, 2025), or new contributions to the domain are regularly published by international organisations, including the national monetary authorities, who issued the selected three CBDCs analysed in this chapter. Example of these changes can be the development of new features or the interoperability of CBDCs with other systems, e.g. the projects supported by the BIS (BIS, 2023a; 2023b; 2023c; 2023f; 2023h; BIS and SNB, 2023). Furthermore, at the time of writing, the selection of CBDCs to be compared as well as the quantitative data on CBDCs, are limited by the scarcity of launched CBDCs across the world, and by the absence of long-term information of CBDCs across the economies, and this may impact the clarity of the scenarios identified, generating uncertainties, affecting the interpretation of the implications of CBDCs on financial systems.

3.1. ANALYSIS OF GLOBAL CASE STUDIES

The CBDCs could reshape the financial infrastructure, from money supply to interest rate policy (WEF, 2020). The main drivers of the implementation of CBDCs vary by country and are also a function of the different economic and social realities. The comprehensive framework developed by the author, as illustrated in Figure 2, groups interrelated variables, thus facilitating a controlled comparison of CBDCs across jurisdictions. By comparing different digital currency solutions, launched in divergent economies and bound to diverse groups of populations, policymakers and national authorities can understand the potential applications of CBDCs and learn valuable lessons. The Bahamas created the Sand Dollar to improve the financial inclusion, especially in its archipelagic country, where banks are scattered across the islands. The Sand Dollar has democratic rules, offering transactional privacy (CBOB, 2019). The Nigeria's eNaira concurs in the attempt to increase financial inclusion, payment efficiency and to reduce the informal economy of the country (CBN, 2021a). The privacy aspects of the eNaira reflect Nigeria's desire to meet regulatory constraints with public confidence. China's e-CNY brings payments modernisation, competition against private payment platforms, and seek to establish digital money sovereignty (PBoC, 2021). The e-CNY is considered a flagship in China's foreign political programme and may prioritise regulatory control, over private schemes (Huang and Li, 2023). The comparison of these three CBDCs, across all variables in the proposed framework, investigates the suitability of CBDCs to cater for a combination of different objectives, and it provides important lessons learned, understanding context-based implementation approaches and required stakeholders' engagement.

At the time of writing, another CBDC was launched but was not considered for the analysis due to a combination of factors, the JAM-DEX (Jamaica Digital Exchange). The research intends to capture a spectrum of possible implementation scenarios, exploring diversity in geography, economy size, and technical approach. The exclusion of the JAM-DEX from the analysis is aimed to avoid redundancy by not including two Caribbean islands' CBDCs with similar contexts. Furthermore, the three selected CBDCs benefit from richer data and literature, as the JAM-DEX has fewer published evaluations compared to the other cases.

The Bahamas comprises over 700 islands, over 30 atolls, and a population distributed geographically, which makes a banking system expensive and hard to establish and maintain. The archipelago nation's small size prevented the expansion of conventional banking, and the Central Bank of the Bahamas (CBOB) introduced its CBDC with the goal of enabling financial inclusion for unbanked and underbanked communities, facilitating the expansion of banking services to the islands of the archipelago, and promoting a fast payment infrastructure. Remotely located banks may lack in-person banking infrastructure, leaving a significant percentage of citizens economically disadvantaged (CBOB, 2021b). The wrath of Hurricane Dorian in 2019 further exposed the shortcomings of traditional banking systems (Rolle, 2019a). Prior to the introduction of the Sand Dollar, nearly 20% of the population had little access to banking facilities (Nguyen, 2024). In October 2020, the Sand Dollar was introduced in the Bahamas, which became the first country to adopt a national CBDC (CBOB, 2020d), with the aim of promoting financial inclusion, particularly for dispersed groups with underserved needs, reducing the cost of services, improving transactional efficiency, and making the payment system more resilient, especially in case of natural disasters (Rolle, 2019b). The Bahamian authorities sought to establish a secure and cost-effective payment system to reduce the burden of distributing and maintaining physical cash on geographically distant islands (CBOB, 2019). Wright et al. (2022) identifies the Sand Dollar as an instrument to promote financial inclusion and modernise the nation's payment infrastructure. CBOB (2019) argue that the success of the Sand Dollar rests on public trust and on the central bank's capacity to address cybersecurity threats. CBDCs can drastically reduce transaction fees, as tourism accounts for over 20% of the country's GDP, decreasing transaction costs would be a great competitive advantage for the Bahamas (Sisodia, 2024). Looking ahead, the Sand Dollar may make the Bahamian economy more resilient, especially in the event of a natural disaster. Hurricanes, for instance, have historically devastated the islands' physical banks. CBDC's availability via smartphone or other digital devices may help the residents of the Bahamas to strengthen the financial ecosystem. By focusing on a social challenge, the Sand Dollar can be classified as a specific implementation with clearly identified goals. Anthony (2025) argues that the CBDC address the logistical issues in offering banking services across multiple

islands, however there is no guarantee that the population may adopt the solutions provided by the governments. The Sand Dollar is powered by a permissioned Distributed Ledger Technology (DLT) system, specifically the NZIA Cortex DLT, provided by NZIA Limited (later rebranded as Movmint), ensuring transaction security (CBOB, 2019). After choosing to develop its operating system on DLT, the transactions executed on the Sand Dollar can be considered secure, auditable and traceable. The Sand Dollar is issued on a parity basis with the Bahamian dollar (BSD), while being anchored to the US dollar to provide stability. Through integration with financial institutions, the Sand Dollar allows consumers to perform transactions via digital wallets, linked to bank accounts (Branch, Ward and Wright, 2023). Financial institutions, payment service providers and retailers are implementing the Sand Dollar into their respective payment systems. The Sand Dollar supports encryption, multi-factor authentication, and continuous monitoring, to ensure resilience against cyber threats, it is mobile-friendly and has an offline functionality to respond to connectivity issues in remote areas (CBOB, 2021b). Through mobile digital payments, the Sand Dollar may help to reduce the use of cash and bank branches, lower transaction fees, make payments more efficient and increase economic activities, in communities with reduced access to cash. The CBOB has adopted a two-tier system that delivers the Sand Dollar via mobile wallets, published by the central bank's Authorised Financial Institution (AFI), who comply with the Know Your Customer (KYC) regulations. Its operating system works online and offline, enabling the possibility to buy products or services or to make transfers, even when internet is not available. The Sand Dollar abides by consumer protections and data privacy regulations, fostering regulatory oversight and public trust (Nguyen, 2024). To achieve its key objectives of financial inclusion and lower transaction costs, there are consumer and business adoption obstacles to overcome. Although financial inclusion holds promise for many Bahamians, there are still important lessons to be learned, when it comes to technology adoption, consumer trust and the protection of privacy (Wenker, 2022). Although, so far, the public has responded positively to the Sand Dollar, particularly in the remote community people that previously did not possess a bank account, its rollout has not been straightforward (Nguyen, 2024). The Central Bank is sponsoring awareness campaigns to educate the public on the features of its digital wallet. Customers were also invited to adopt Sand Dollars as a part of existing banking processes and electronic payment services in everyday life. The CBOB has announced that it is working on improvements to interoperability with all payment methods, strengthening its compliance mechanism and promoting awareness campaigns, to develop user confidence and to increase the adoption rates across the archipelago. The CBOB has also established a multilateral approach (CBOB, 2020b) to cooperate outside the country. This implementation can illustrate the impact of CBDCs in small economies, with a distributed population and a potential to grow regionally in the Caribbean Community, a two-tier distribution model, a simple technological

solution using blockchain with no programmability, and a balanced approach between privacy and regulations.

With cash as payment medium of choice for its population, Africa's largest economy by GDP Nigeria launched the eNaira in October 2021, making it the first African nation to implement a CBDC. The eNaira may become an important instrument to modernise its financial industry and to tackle structural challenges of large informal economy, financial literacy and accessibility (CBN, 2021a). The eNaira is expected to promote economic growth by facilitating government payments, by encouraging financial inclusion through ease of access to financial services, by cutting costs for payments, by facilitating remittances which are a source of income for many Nigerians, by enhancing payment efficiency and monetary policy effectiveness, and by absorbing informal economic activity into the financial system (CBN, 2021a). According to Adegbite and Aremu (2022), the eNaira may be capable of reducing the cost of cash-handling, improving cross-border trade. The authors add that it might also reduce illicit money flows. Sadat and Shaba (2025) identify some of the eNaira's susceptibilities in public trust and people's digital literacy. The researcher highlights the need for education and open policies among the public to foster adoption. These issues may be tackled by the CBN through a proactive communication programme and policy alignment. The eNaira is built on a private permissioned DLT platform, which was created by Bitt Inc, a fintech company with experience with CBDC applications (Atlantic Council, 2025). The eNaira is administered by the CBN, with access given to the public and partner banks (CBN, 2021a). The platform adopts a hybrid technology, based on centralised CBN's administration, with distributed ledger functionalities, providing security and transaction efficiency. Customers can use eNaira with Unstructured Supplementary Service Data (USSD) codes for transactions with feature phones, along with mobile applications, with simplified access and easy adoption methods, catering for different levels of technological accessibility (Hamza, Farouk and Ahmad, 2023). It utilises encryption and secure authentication methods to protect transactions (CBN, 2021a). The eNaira places a heavy emphasis on interoperability with the existing financial services, supported by biometric security features. The platform can execute safe payments and supports integration with current banking systems. One of the technological issues of the eNaira comes from Nigeria's fragmented digital system, as the adoption rate is impacted by the limited technological infrastructure. The Nigeria's intermittent internet connectivity and low-level digital literacy have implications for user adoption (Sadat and Shaba, 2025). Offline capabilities are important to the CBN, however limited infrastructure development might hinder its adoption. This implementation can demonstrate the impact of CBDCs in medium-sized economies, with a population overseas interested in cross-border remittances, a two-tier distribution model, an intermediate technological solution using the permissioned DLT

Hyperledger Fabric platform, support for programmability and a multi-tiered KYC approach that enables anonymity.

China experienced increased digital payment adoption during its economic expansion of the past years, also in virtue of private platforms like Alipay and WeChat Pay. In 2020, the PBoC introduced the e-CNY, with the objectives to strengthen financial oversight and to modernise the payment systems, increasing monetary sovereignty and reducing dependence on private platforms (PBoC, 2021). The e-CNY may serve as a digital substitute for cash, to complement the physical currency in circulation (Li and Huang, 2021), acting as a payment network, enabling a smoother and closer control of the financial system (Zheng, 2023). The PBoC sought to improve control on money supply, circulation and on payment systems, currently largely in private hands. Furthermore, on a geopolitical level, the e-CNY might support the internationalisation of the Renminbi, strengthening its role as medium of exchange in global trade and international finance, eventually serving as a viable alternative for payments and settlement of trades in global markets. According to Bansal et al. (2021), the e-CNY might help to enhance China's currency internationalisation prospects, by reducing the dependence on the US dollar for global trade (Caudevilla and Kim, 2022). Political analysts suggested that the e-CNY may allow the Chinese authorities to enforce compliance over payments and to promote a state-backed alternative to cryptocurrencies (Alonso-Trabanco, 2025). Cheng P. (2022) challenges the privacy aspects, as the central bank's ability to examine transactions might create an increased level of monitoring. The pilot projects signal solid government backing and infrastructure readiness. The e-CNY works in a hybrid framework, but unlike cryptocurrencies which are governed by a blockchain (an irreversible public ledger of all confirmed transactions), the e-CNY is governed by a centralised ledger, operated by the PBoC. The distribution scheme follows a structure in which the central bank mandates the distribution to authorised financial institutions.

The e-CNY employs two-tier mechanism in which the central bank issues money to existing banks and payment networks, who distribute it to citizens thereby maintaining the current financial intermediation model, while introducing the digital currency (Li and Huang, 2021). This CBDC is intended to be compatible with the existing payment infrastructure, for maximum accessibility. The e-CNY can be used both online and offline, with no internet access required to make a transaction. This is a key factor as the digital divide continues to be experienced in rural China, where technical infrastructures are being set up. The key features include the possibility to perform dual offline payments, a controllable anonymity mechanism providing privacy, a powerful programmability via smart contracts for conditional purchases, and support for existing digital wallets, such as Alipay and WeChat Pay, to enable users to exchange it

more conveniently. This functionality is enabled in the e-CNY via Near-Field Communication (NFC) function and secure hardware modules on the device (Cheng P., 2022). While it increases usability, this feature might introduce security concerns in terms of synchronisation and double spending, once the devices are reconnected to the network. In fact, offline transactions enable users to perform payments without an internet connection; however, this may lead to potential security risks of double-spending and fraud (Cheng P., 2022). With its CBDC launch, the PBoC can take advantage of new tools in monetary policy (Zheng, 2023) and might adopt a stronger approach to regulate inflation and to reduce shocks to the economy. The e-CNY's digital aspect allows for better oversight (Kshetri, 2022). The e-CNY holds the potential to serve as a financial data resource, empowering authorities to track financial activities with greater precision (Li and Huang, 2021). Transaction cost can be lowered for digital currencies, especially for cross-border payments. The reduced cost for digital transactions could be applicable to both domestic and foreign transactions for companies and consumers (Caudevilla and Kim, 2022). The traditional banking system includes many intermediaries with multiple layers of fees. CBDCs transactions could be executed in a faster way when compared to the system used by conventional banks.

An increased transaction speed produces significant benefits for the private and public sectors. Digital currencies may be subject to technical threats such as cyberattacks and system malfunctions (BIS, 2023g), which may undermine public trust in innovative technology. Like all digital systems, CBDCs could be hacked or impacted by outages, although digital currencies should be designed in a highly secured manner. The e-CNY is expected to extend financial services to the estimated millions of people who do not yet possess an account in the traditional banking system (Chin, 2025). Improved accessibility to distant rural areas and to unbanked and underbanked groups may promote the country's financial inclusion agenda (Li and Huang, 2021). Although digital currencies can facilitate financial inclusion, they might also exclude ordinary people who do not have access to the necessary technologies, creating artificial barriers in accessing their funds, and intensifying social disparities. Psychological and cultural barriers could delay the rate of adoption, as corporates and consumers may be hesitant to adopt the new technology and form of payment. The degree of public acceptance seems high, likely because Chinese citizens are used to digital payments through other platforms, given the popular and widespread use of different local digital payment providers. The PBoC promoted the pilot projects and incentivised the public to use e-CNY. However, the e-CNY competes with all the established private payment platforms that have already become deeply embedded within the Chinese daily life, for instance Alipay and WeChat Pay. For the e-CNY to become the payment platform of choice, the PBoC should continue with the incentive policies, fostering its integration into public and commercial payment systems and into the

major Chinese tech platforms (Subrahmanyam, 2023). Its interoperability with international financial systems, could also become a competitive advantage, as China may aim to promote the global adoption of this currency (Bencivelli and Savini, 2023). In consideration of its technological investments and policy initiatives, the e-CNY may be launched nationwide in the near future. It may be possible to argue that China's notable advance in the CBDC development could reflect the country's ambitions to become a global currency. The e-CNY can facilitate and accelerate international trade and investment, complementing the US dollar in international settlements, in line with China's Belt and Road initiative (Caudevilla, 2022).

Until recently, the Federal Reserve took tangible steps to implement its own digital money, but the executive order issued by the President of the USA on the 23 January 2025, outlawed all operations regarding the development of a CBDC within U.S. territory with immediate effect, with the motivation that they may pose threats to financial stability and personal privacy (The White House, 2025). A wider adoption of the e-CNY could have the potential to bypass payment systems such as SWIFT (Chorzempa and Spielberger, 2025), potentially posing risks to the compliance with international sanctions, which are enforced at international level through the established payment systems. Meanwhile, other countries may not decide to use a CBDC payment system, in cross-border trade, due to sovereign concerns. CBDCs could create another battlefield for international rivalry and regional hegemonic competition. In consideration of factors such as the scale of transactions and the complexity of running multi-currency CBDCs arrangements, the internationalisation of the e-CNY may be gradual, at least in the initial phase (Bencivelli and Savini, 2022).

In conclusion, the e-CNY may offer efficiency, cost-savings and opportunities to strengthen controls, but it might generate reflections about data privacy and raise potential geopolitical concerns. This digital currency can demonstrate the impact of CBDCs in large economies, with vast population, large processing volumes and cross-border potential. It has a two-tier distribution model, a custom technological solution using a centralised platform with advanced programmability, and a dual offline wallet system, ensuring full compliance. A detailed comparison of the three CBDC implemented, across all the variables identified in the proposed framework, is available in the next sections of this paper.

A. POLICY REGULATORY AND GOVERNANCE

3.1.1. MONETARY POLICY

CBDCs may enhance the efficacy of monetary policy, since they give central banks access to economic information in real time, and novel instruments to implement monetary policy (Mancini-Griffoli et al., 2018). CBDCs may enable central banks to collect real-time transactional data that can be used to produce more accurate economic forecasts and more precise policy making (Das et al., 2023). The information gathered may enable a more flexible and efficient monetary policy action, while the existence of programmable functions may support new policy measures (Kiff et al., 2020). The extent of the impact of CBDCs on monetary policy varies, depending on the user uptake and the integration of digital currencies in the wider economy (Prasad, 2021).

The Sand Dollar has given to the CBOB greater access to implement monetary policy through real-time information about money circulation and more accurate forecasting capabilities. The Sand Dollar supports the implementation of direct monetary policy interventions, as the CBOB may be able to digitally adjust the supply of money, facilitating the monetary policy transmission (CBOB, 2019). This capability is specifically important in a highly distributed geographical context (Wright et al., 2022). However, its lack of programmability cannot contribute to the dynamic monetary policy fine-tuning. The dependence from cash for large groups of the population, constrained the effectiveness of the Sand Dollar as a lever to adjust the aggregate demand and inflation monitor. Due to its small scale, its influence on international monetary policy is limited. Researchers such as Wright and Todd (2022) argue that while CBDCs such as the Sand Dollar increase transactional transparency, their impact on more general monetary goals is modest in small open economies. Hence, although the Sand Dollar is a promising instrument to achieve financial inclusion, its effect on monetary policy may be, at present, moderate.

The eNaira facilitates monetary policy by offering timely data collection and direct interventions in the money supply (CBN, 2021a). Nigeria created the eNaira to act as a tool to facilitate monetary policy effectiveness and to enhance financial inclusion (CBN, 2022). The eNaira can enable direct welfare payments and faster tax collection, minimising errors in processing, thus facilitating fiscal management (Obiora, 2023a). Through the eNaira, the circulation of money can be directly controlled, supporting a cost-effective management of physical cash, permitting the central bank to better manage inflation. The eNaira shows Nigeria's determination to tighten monetary regulation, to restrain the dominance of volatile cryptocurrencies, and it

allows the CBN to make targeted social interventions in specific areas (Chukwuere, 2021). The central supervision of the eNaira might help the government to maintain control over monetary transactions, minimising capital outflows and improving financial openness. The centralised architecture of the eNaira may influence Nigerians' trust in CBDCs, as residents may be wary of potential state intervention in personal funds. The intermittent internet connectivity and people's reliance on cash for transactions, may limit the potential for the eNaira as an effective monetary policy instrument (Idisi et al., 2024). These difficulties may limit eNaira's scalability and might constrain its role in achieving monetary policy objectives, especially in inflationary regions, where cash prevails.

The e-CNY is designed to facilitate the monetary policy operations through faster and more precise transaction execution and data collection (PBoC, 2021). The e-CNY allows the PBoC to monitor money velocity, increasing the number of monetary tools available to the central bank. The e-CNY establishes China as a leader in digital currency innovation, with the potential to challenge other important currencies (Chorzempa and Spielberger, 2025). The e-CNY works through an advanced two-tier distribution mechanism that enables the PBoC to issue digital currency to traditional banks, which in turn distribute it to the end users. This mechanism supports the respect of monetary sovereignty, allowing the PBoC to use transaction data for targeted policy interventions, like interest rate adjustments and liquidity management (Cheng P., 2022). The PBoC maintains control over the money supply, may gather and analyse data for more accurate policy decisions, fine-tuning interest rates and managing international settlements (Jiang and Karman, 2023). The e-CNY's programmability introduces new tools for monetary policy, technically allowing the PBoC to restrict the possibility of spending funds in specific categories of goods and services over a predefined timeframe (Yang and Zhou, 2022). This can become a sophisticated instrument of monetary policy, whereby the PBoC (2022) could address issues on a currency circulation and improve consumer welfare. Critics argue that the e-CNY influence over the financial system, may increase the risks of privacy and surveillance (Fanusie and Jin, 2021). The e-CNY may create privacy concerns, and authors such as Fanusie and Jin (2021) believe that this topic might discourage its adoption.

The Sand Dollar and the eNaira are focused on domestic economic stability and financial inclusion, with potential cross-border ambitions limited to the regional areas. The Bahamas and Nigeria consider their CBDCs as a way of strengthening monetary sovereignty, reducing the reliance of residents over cash and private cryptocurrencies. China has included the e-CNY as part of its Digital Silk Road plan, with ambitions to expand the role of its CDBC, as an alternative currency in cross-border transactions (Caudevilla, 2022). By internationalising the

e-CNY, China may broaden its monetary sovereignty and reduce its dependency from foreign currencies. The analysed CBDCs may not be equally effective at executing monetary policy, with the e-CNY being the most advanced, due to its innovative features and high adoption rates. The e-CNY can help to enhance the policy transmission system, while the Sand Dollar and eNaira can be used to manage the money supply and to combat illegal transactions (CBOB, 2019; Ikidi and Okoh, 2025). As CBDCs develop further, future studies may be necessary to analyse the impact on CBDCs of flexible monetary policies, targeted incentives and international partnerships.

3.1.2. *FINANCIAL STABILITY*

Financial stability refers to the ability of financial intermediaries including banks and payment providers to endure economic shocks without damaging the financial system. Traditionally, central banks controlled financial stability through monetary policy operations, banks' oversight, and by maintaining the currency supply. In the case of CBDCs, these activities are evolving, requiring new approaches to limit the risks, harnessing the benefits of digital finance. CBDCs may contribute to financial stability, by simplifying payment habits, introducing a more direct money supply and delivering new monetary policy instruments. In fact, CBDCs have the potential to boost the financial stability, giving central banks direct instruments to control money supply and interest rates (BIS et al., 2021b). Researchers claim that direct access to central bank liquidity may lower commercial banks' deposit base, impacting their lending capacity (Wenker, 2022). Agur et al. (2019) argue that disintermediation risks may depend on the CBDC design, as interest-paying CBDCs might drive deposits away from traditional banks more than non-interest-paying CBDCs. Auer, Cornelli and Frost (2020) claim that CBDCs could promote resilience, by introducing an alternative currency in situations of crisis, allowing central banks to have greater control over the monetary system. CBDCs may consolidate economies, by bringing transparency into the informal economy, allowing more accurate fiscal measures. Bossone (2022) highlights the financial inclusion capabilities of CBDCs, especially important for economies with unbanked and underbanked populations.

The Sand Dollar may be considered as a stability tool, specifically focusing on the financial inclusion of underserved communities. The regulatory framework of the Sand Dollar is built around consumer protection, while maintaining public confidence. Economically, the Sand Dollar may reengineer the Bahamian payments infrastructure. Cash processing is costly, and digital transfers may be more appealing to end users (Di Iorio et al., 2025). The Sand Dollar shows the government's willingness to help the unbanked and underbanked populations (Wright et al., 2022). Financial crime could also be prevented by reducing the reliance from

physical cash (CBOB, 2020b). In technology terms, the high mobile penetration in the Bahamas supports the CBDC adoption through mobile wallets (Branch et al., 2023). The DLT technology provides the integrity and security of transactions, crucial to build confidence among users (CBOB, 2019). However, infrastructural limitations in remote islands affect the CBDC network's capacity and stability (Sisodia, 2024). Preferences for cash and low levels of digital literacy may represent barriers to widespread adoption (Branch et al., 2025).

The eNaira can supplement cash and existing electronic payment systems to provide the CBN with better instruments to control the money supply (CBN, 2021a). Greater monetary policy capacity could also reduce inflationary risk (Ikidi and Okoh, 2025). The eNaira can be considered as a tool to reduce corruption and to generate more revenues for the government (Ozili, 2023c). Payment transparency can facilitate anti-corruption efforts (Suoye, Nnaemeka, and Itotenaan, 2022). The eNaira minimises the dependence from third-party payment systems and increases economic autonomy (Obianwu and Okwor, 2022). It may reduce fees for domestic and international payments (Idisi et al., 2024). According to the CBN (2023d), the eNaira has been primarily used as an option for payments, rather than as significant alternative to physical cash. Its effects on stability are influenced by its implementation and public acceptance. Despite its potential to integrate Nigeria's informal economy and to facilitate inexpensive and faster cross-border payments, which are relevant for Nigeria's diaspora (Suoye, Nnaemeka, and Itotenaan, 2022), adoption rates have been moderate, potentially affecting wider financial stability indicators, such as inflation and interest rates. The intermittent internet connectivity and the power supply issues in Nigeria might affect the availability of CBDCs to users (Chukwuere, 2021).

The CBDC allows the PBoC to apply policies directly and more effectively, with an efficient real-time tracking of money flows (Shen and Hou, 2021). It may facilitate a faster transmission of monetary policy (Huang and Li, 2023). With its centralised ledger, the e-CNY's enables control over its allocation and usage, enhancing cybersecurity and fraud prevention. The system may guarantee safe payments and prevent phishing risks (PBoC, 2021). The e-CNY is integrated with existing payment systems and traditional banks (Huang and Li, 2023). The government hopes to undermine the dominance of private tech companies in the payment area, by offering an advanced digital currency (Xia, Gao and Zhang, 2023). Other countries may also hesitate to adopt the e-CNY because of geopolitical considerations (Bansal and Singh, 2021). The cashless payments of the e-CNY will help the government avoid physical cash handling expenses (Siu, 2023). The CBDC lets the government closely monitor money circulation, which helps to establish improved regulatory transparency and measures, to maintain financial stability, according to Mu (2023).

Each of the three CBDCs have the potential to improve financial stability, by enhancing monetary policy instruments and payment mechanisms, although each implementation approach is different. The Bahamas uses its CBDC to reach the unbanked groups of population, Nigeria aims to bring transparency into the informal economy, and China adopts the e-CNY to consolidate its leadership in digital payments (CBOB, 2019; CBN, 2021a; Bencivelli and Zangrandi, 2023). Periodical assessments of local conditions remain essential to minimise risks and to achieve the full potential of this innovation.

3.1.3. LEGAL ACCOUNTABILITY

One of the key differentiators between privately issued digital currencies and CBDCs is the implementation of a clear legal framework to discipline the CBDCs, as this provides the basis for the public adoption (BIS et al., 2024). CBDCs are subject to national laws and regulations, which emanate from each country's economic, political and legal priorities.

The Sand Dollar was set into the pre-existing financial regulatory framework, with adjustments to refer to digital currencies. The Sand Dollar's legal foundation is outlined in several laws. In the CBOB Act there is the legal authority for the CBOB to issue money, including digital currencies (CBOB, 2020a). The Banks and Trust Companies Regulation Act regulated the financial institutions. The Payment Systems Act and Payments Instruments (Oversight) Regulations, which define payment services and applicable rules, were updated to include digital currencies, and to regulate payment service providers that participate in the Sand Dollar operations (CBOB, 2021d). The Sand Dollar is regulated by strict data protection legislations i.e. the Bahamian Data Protection Act. The CBOB has established rules and regulations to ensure that the Sand Dollar is backed by an effective legal and regulatory framework. The Sand Dollar's Regulatory Framework defines the participants' obligations, compliance requirements, and consumer protection guidelines (CBOB, 2020b), and the Counter-Terrorism Financing (CTF) rules and the Anti-Money Laundering (AML) regulations that require transactions to meet international standards to prevent illicit activities (CBOB, 2021d). The Central Bank of the Bahamas Act and Payment Systems Act were revised to grant the CBOB regulatory control over the issuance of digital currency, to ensure its safe and legal use. The CBOB provided detailed guidelines to the Authorised Financial Institutions (AFIs), such as traditional banks, credit unions, and payment service providers of the Sand Dollar ecosystem. These regulations concern customer due diligence, data privacy and cybersecurity measures that ensure that the CBDC functions with a robust legal and regulatory framework (CBOB, 2020b). The interface between Sand Dollar and the existing banking systems allows for frictionless transactions and facilitates adoption (CBOB, 2021e). Studies show that Sand

Dollar's legal framework focuses on financial inclusion, and researchers highlight potential compromises between the protection of privacy and compliance (Wenker, 2022).

The Central Bank of Nigeria Act received amendments to establish the eNaira's regulatory framework which permits the CBN to issue currencies as legal tender and set monetary policy guidelines. The AML and CTF Compliance Framework was developed to ensure the entire eNaira ecosystem complies with the nation's financial crime rules as well as international regulations (CBN, 2021b). The regulatory framework of financial institutions, disciplined under the Banks and Other Financial Institutions Act (BOFIA), needed to be modified to authorise the digital currency circulation. The CBN established the eNaira Regulatory Guidelines to define the necessary policies and procedures along with dispute resolution methods and consumer protection regulations and to outline the responsibilities of banks, merchants and users thereby ensuring transparency and compliance (CBN, 2021a). Other regulations include Nigeria's Data Protection Regulation (NDPR), which brought guidance on privacy matters, although some researchers have observed grey areas, related to data privacy and security, as specific policies might be needed to manage certain risks related to CBDCs (Omotubora, 2024). The Consumer Rights rules provide robust dispute resolution mechanisms and protect users against fraud and abuse (CBN, 2021b). The laws pertaining to the eNaira focus on KYC and AML verification but also address unique local issues regarding the informal areas of the economy.

China has updated its legislation to introduce its digital currency as legal tender, and to ensure compliance and compatibility with existing financial systems (PBoC, 2021). The legal foundations of the e-CNY were established through different laws. The Law of the People's Republic of China on the PBoC enables the PBoC to issue and control money (Lu and Chen, 2021). The Law on the PBoC was amended to introduce digital currency with equal legal status with physical money, thus enforcing its acceptability (Xu and Jin, 2025). The Regulatory Guidelines on the management of digital currency disciplines the issuance, circulation, and anti-counterfeit measures. Its legal framework includes compliance with regulations related to AML, CTF, data protection, and cybersecurity. The PBoC retains the right of supervision of the transactions executed to verify compliance. The e-CNY enforces comprehensive arrangements, which are aligned with China's overall digital governance agenda (Cheng P., 2022). The PBoC framed the e-CNY to ensure data security, and according to some researchers, this may originate concerns over privacy matters (Fanusie and Jin, 2021). Researchers argue that the efficiency of the e-CNY may not impact the innovation in the private sector, and the private efforts in the digital payments area (Fullerton and Morgan, 2022). Other authors believe that the e-CNY may bring equality of opportunity, by creating a

public alternative to private platforms, encouraging competition and choice (Huang et al., 2023). Authors have also highlighted other potential barriers, such as the need to improve confidence in the financial system (Cheng P., 2022). The success of the e-CNY may be reinforced by the ability of the country to address the concerns raised, and to strengthen international cooperation.

The three countries have all amended, in varying degrees, their regulations to introduce their CBDCs. Legal tenders such as the Sand Dollar, eNaira and e-CNY reflect their national regulatory approaches and economic priorities. The Bahamas and Nigeria reformed the existing legislation to integrate the digital currency, to give to their CBDC legal tender status (CBOB, 2019; CBN, 2021a). China has adjusted its regulations to enforce the e-CNY's legal status and to respond to regulatory challenges (Lu and Chen, 2021). China's model ensures supervision and puts emphasis on financial stability and monetary sovereignty (PBoC, 2021). The three jurisdictions demonstrate compliance with AML/CTF standards. The Bahamas and Nigeria aim towards regulatory compliance, while safeguarding personal freedoms according to CBOB (2019) and CBN (2021a). China's advanced technological solution may enforce regulatory compliance and transaction oversight (Wang, 2022). These case studies represent key learning points for central banks exploring CBDCs' issuance.

3.1.4. TRANSITION STRATEGY

According to Prasad (2021), CBDCs may be able to streamline financial systems, by decreasing reliance to cash and by incentivising digital money payments. Other researchers point to potential pitfalls. Auer et al. (2022) argue that, if not planned correctly, the transition from cash may raise concerns among specific groups of people, especially the low-income groups or residents in remote areas, who are used to execute payments through physical cash. Hence, when planning their transition strategy, central banks should allow sufficient time to enable a gradual transition from cash, not to marginalise vulnerable groups. The Bahamas points to the complementarity of the Sand Dollar with their physical currency, similarly to the parallel circulation objective assigned to the eNaira, which is supported by awareness campaigns. China might opt for a gradual replacement policy. Such variations are indicative of different national priorities between modernisation and regulatory oversight.

Researchers argue that the Sand Dollar can be instrumental to resolve the ineffectiveness in the distribution of physical cash across the islands in the Bahamas and to perform payments in rural locations, where banks are not available (CBOB, 2019). The Sand Dollar has an objective to enable financial inclusion helping the government to reach people in underserved

communities, without relinquishing the current physical cash infrastructure. The Bahamas have embedded in their legislation the principle that cash will continue to remain a mean of payment, to allow residents to continue to perform cash payments, thus minimising potential resistance to the national CBDC (CBOB, 2021d). The Sand Dollar's distribution model conforms to the Bahamian government's mandate of strengthening economic sovereignty, without sacrificing state regulation or privacy (Sisodia, 2024). Its distribution model delegates the control of user data to private financial institutions, partially resolving privacy issues. The transition strategy indicates an incremental roll out of the Sand Dollar, allowing residents to gradually introduce the digital currency, without completely replacing cash (CBOB, 2019). This gradual move acknowledges the residents' preference for cash, while proposing a valid alternative. By complementing the use of cash through its CBDC, the Bahamas deflated resistance to CBDC adoption and opted for a voluntary changeover (Nguyen, 2024). Moreover, its gradual implementation has reduced residents' fears about potential surveillance. The Bahamas decided for a gradual approach, letting users select their preferred payment option, between cash and the Sand Dollar.

Nigeria's transition strategy is centred on the parallel circulation of the eNaira with physical cash, prioritising training and users' adoption of the digital currency (Adegbite and Aremu, 2022). Nigeria's informal economy, dependent on cash transactions, does not enable state authorities to fully enforce tax laws and financial regulations. With the introduction of the eNaira, Nigeria intends to curb cash inefficiencies, reducing transaction costs and decreasing financial crime (CBN, 2021a). One of the main purposes of the eNaira is to reduce the country's informal economy by offering a digital payment instrument to minimise cash dependence, and to boost financial transparency (CBN, 2021a). Observations reveal that its offline functionality is a key feature for inclusivity (Idisi et al., 2024). Researchers argue that the eNaira's strength is to provide Nigerian residents with a secure mean for payments, reducing money laundering risks and fostering financial inclusion (Esoimeme, 2021). The eNaira may facilitate remittances, by lowering transaction fees (Idisi et al., 2024). Researchers have suggested that the eNaira could promote financial inclusion (Akpan et al., 2024). The Nigerian government intends to increase financial transparency and to curb informal cash transactions, through the introduction of its digital currency. Trust issues might remain, impacting adoption rates, as users may associate the digital currency to a greater state surveillance, or they may have fears over the security of the CBDC (Idisi et al., 2024).

The PBoC opted for a progressive path for the e-CNY implementation. Pilots in 2020 started in Shenzhen, Suzhou, Chengdu, and Xiongan, and included lotteries, partnerships with traditional banks and payment providers, according to Kshetri (2022). The e-CNY was also

introduced to pay daily expenses, such as public transportation, payments at retailers and public services (Jiang and Karman, 2023). The pilot phase aided in the testing of technical protocols, in user interface enhancements, and to address security issues. The usage of the e-CNY has been promoted by the Chinese government through incentives at different levels, for consumers with cashback campaigns, discounts, promotional offers (Subrahmanyam, 2023), for merchants with reduced transaction costs compared to private payment providers and for public entities for tax, governmental fees, and subsidy payments (Branch et al., 2025). The e-CNY follows a two-tier system in which the central bank issues the digital currency and sends it to specific entities such as commercial banks and payment networks (Subrahmanyam, 2023). These intermediaries help to onboard users and to promote the e-CNY in existing financial networks. The e-CNY platform is technologically advanced, with a dual-offline payment system that is fully functional without internet access (Mu, 2023). The e-CNY enables online transactions, diminishing the reliance to cash and improving the monitoring of transactions, a measure some economists state that may support economic oversight but might challenge privacy (Tonnier and Qiu, 2024). By encouraging digital payments, the e-CNY provides authorities with better data about domestic consumption and can become an alternative to private digital payment platforms, like Alipay and WeChat Pay (Papadavid, 2021). The rise of the e-CNY under China's dual circulation plan coincides with China's policy goal to modernise its domestic economy through digitisation and to lessen the dependence on the global financial system (Fullerton, 2022). China introduced incentives to promote the e-CNY's use as alternative to cash. While this model encourages adoption, it should take care of less tech-savvy people, who may be dependent from cash (Chin, 2025).

The Sand Dollar provide residents with a digital alternative to cash, without depriving individuals of their freedom of choice. The Sand Dollar is perceived as an alternative to cash; however, cash is still widely used for ordinary purposes. The Nigeria's eNaira shows the complexity of implementing a CBDC among open uncertainties and infrastructural constraints. China's e-CNY is actively promoted, also by means of lotteries, to substitute cash payments (Sun, 2021). The Sand Dollar, eNaira and e-CNY demonstrate how different transition strategies, being the product of several national priorities and socioeconomic conditions, can contribute to the deployment of digital currencies, through unique economic, political and technological objectives.

3.1.5. REGULATORY OVERSIGHT AND ETHICAL IMPLICATIONS

The rollout of CBDCs has entailed considerable regulatory adaptation within the involved countries. Regulations, in both the Bahamas and Nigeria, aimed at reducing security risks

and at improving the stability of digital currencies, challenging fraud and increasing financial inclusion. China's regulatory initiatives were more profound, with the PBoC striving to build an infrastructure capable of handling both domestic and cross-border payments (Saliya, 2025). The researchers argue that these distinctions reflect each nation's different political and economic interests, and influence how CBDCs are designed and regulated. Periodical adjustments to the regulatory framework may be needed to respond to new technological and financial risks (Wang and Gao, 2024).

The Sand Dollar is part of a wider program to increase financial accessibility throughout its archipelagic state (CBOB, 2021b). The CBOB controls the issue and circulation of the Sand Dollar and ensures that it aligns with monetary policy goals. The CBOB maintains an active regulatory control over the Sand Dollar, advertising it as a government-backed digital currency, protected from money laundering and fraud. Data privacy and autonomy for users are at the core of the Sand Dollar's regulatory approach. The Sand Dollar has reinforced regulatory oversight, supporting the country's efforts to combat financial crime (CBOB, 2020a). The CBOB has a regulatory approach focused on consumer safety, data security, and alignment with international AML and CFT standards, meeting international guidelines of the Financial Action Task Force (FATF) (CBOB, 2021d). The Sand Dollar focuses on privacy protection and relies on KYC validation, via regional banking partnerships (Haans, 2024). The CBOB has implemented a three-tiered KYC process to strike a balance between ease of use and regulatory compliance. This model enables those without formal identification to take advantage of basic financial services, while reducing risks of money laundering and fraud (CBOB, 2021d). The CBOB has implemented rigorous privacy measures, preferring a model that minimises personal information collection, while providing transactional traceability, in line with AML and CFT guidelines. This compromise is intended to both protect the privacy of users and to ensure regulatory adherence and it stands in stark contrast to other CBDCs (Nguyen, 2024). This model is viewed as a step toward financial inclusion, because it offers a simplified access, without the need to share detailed personal information. The Sand Dollar has been praised for safeguarding freedoms, and it is consistent with the Bahamian government's ambition of financial inclusion, without excessive surveillance (Sisodia, 2024).

The Nigerian legal system focuses on supervision and financial stability. Its regulatory environment strives to maintain a good mix between innovation and economic stability and safety. The CBN oversees the eNaira with a focus on financial inclusion, consumer safety and compliance to AML and CFT rules (CBN, 2021b). The CBN has tiered levels of KYC that made user onboarding easy, ensuring regulatory compliance (CBN, 2021a). However, research indicates that adoption rates remain constrained by digital illiteracy and

infrastructural issues (Chukwuere, 2021). With limited data collected, the eNaira's design is meant to preserve the autonomy of individuals and companies, but digital infrastructure vulnerabilities might make it subject to potential vulnerabilities. Suoye, Nnaemeka, and Itotenaan (2022) states that the success of the eNaira's privacy measures, rests on the CBN's capacity to strengthen Nigeria's digital infrastructure. Researchers stress the need for privacy controls to encourage users' trust (Victor, 2025). Akindipe, Akhimie and Olonade (2023) advocate for a stronger regulatory framework, arguing that higher compliance could improve user trust and support international operations. The eNaira runs on Nigeria's regulatory landscape with its high informal economy and limited penetration of banking services.

The e-CNY embodies the nation's commitment to digital sovereignty and to compliance to regulations with sophisticated, multi-layered security architecture that give priority to data management and supervision (Mu, 2022). Its implementation reflects China's unique socio-political context, where compliance is seen as critical to social stability and national security (Biedermann et al., 2022). The e-CNY seeks to improve China's security through monitoring capabilities, to prevent illicit activities and to combat financial crime (Kshetri, 2022). Through digitisation, China seeks to reduce the anonymity of cash transactions, increasing control on payments, which some critics say it might affect privacy (Fanusie and Jin, 2021). Experts suggest that this enables greater economic stability and supports China's vision for a robust digital economy, while potentially limiting privacy (Jiang and Karman, 2023). The e-CNY represents an effective mean of oversight, compatible with the broader objectives of social governance (Prasad, 2022). The PBoC holds significant influence over the distribution, usage and monitoring of the e-CNY in line with China's financial control (Xia, Gao and Zhang, 2023). The centralised nature of the e-CNY may enable the access to insightful data about transaction patterns. Fanusie and Jin (2025) argue that the Chinese control over e-CNY transactions might facilitate monitoring and data tracking, with concerns over privacy. The e-CNY's architecture expresses a compromise, where national security is balanced with personal privacy, a position discussed in the literature. The e-CNY adopts a tiered wallet system, where higher levels of identification with more rigorous KYC screening, permit higher transaction limits (Li and Huang, 2021). Cheng P. (2022) informs of the obligation to deter financial crime and to balance the protection of privacy with the prevention of financial crime. The implementation of the e-CNY could also be analysed under a geopolitical perspective, putting China at the forefront of digital finance. Peruffo et al. (2024) believe that, by making the e-CNY an alternative to current global trade currency reserves, China could improve its economic power, further influencing world monetary standards. It is this strategic aspect that sets the e-CNY apart from other CBDCs and strengthens its impact on China's monetary policy system.

All three CBDCs analysed have a strong focus on regulatory compliance, particularly to AML and CTF rules. The level and types of monitoring vary, depending on the regulations and governance of the adopting country. The Sand Dollar is known for its commitment to financial inclusion and user privacy. Since user autonomy and accessibility are the core priorities of the Bahamas' regulatory environment, the Sand Dollar represents a precedent for CBDCs designed to encourage economic engagement between geographically separated communities. Although this architecture maintains integrity, it depends on continuous investments in digital infrastructure to support secure transactions at high volumes. The adoption and use of eNaira operate within a legal framework that promotes financial inclusion, but infrastructure and cyber security might remain problematic. The CBN implemented data protection and economic inclusion measures, which may benefit residents, as soon as the infrastructural and digital literacy issues will be resolved. To increase the eNaira adoption the Nigerian government should build consumer trust. The e-CNY prioritises security and regulatory aspects, thereby contributing to the promotion of national security and social stability. This comparative study demonstrates the complexity of CBDC regulatory frameworks. Regulations significantly shape the economic impact, political goals and technology. The expected positive social impact of CBDCs involve privacy protection, financial inclusion initiatives and socio-economic development outcomes. CBDCs rely on a delicate equilibrium between personal freedoms and the regulations required to ensure human rights and financial system stability.

Regarding the Policy, Regulatory and Governance Dimension, the e-CNY stands out for its programmability and advanced policy tools, while the Sand Dollar and eNaira are more defined by local conditions and available infrastructure. All three CBDCs aim to improve monetary policy transmission and to have an impact on their regions, but only the e-CNY has significant international capabilities. Each project must address local stability challenges, for instance financial inclusion in the Bahamas, or transparency and legality in Nigeria, and regulatory oversight in China. Adoption rates and infrastructure constraints emerge as improvement areas for the Bahamas and Nigeria. The three countries modified their legal frameworks to enable the issuance of CBDCs, introducing modifications in privacy and oversight areas. Inclusion and consumer protection aspects were prioritised by the Bahamas and Nigeria, and China focused on compliance, security and innovation. Gradual, inclusive approaches are common across the three countries, with cash remaining a national instrument available. The strategy adopted by the Chinese Authorities has been more effective, with incentives and innovative technology to increase the adoption rates and the security of the developed solution. National priorities and values are reflected in the implementation of each country,

with compromises between privacy, inclusion, and regulatory oversight. The table below represent the key differences across the three CBDCs.

TABLE 6: COMPARATIVE ANALYSIS OF THE POLICY, REGULATORY AND GOVERNANCE DIMENSION

Dimension	Sand Dollar	eNaira	e-CNY
Monetary Policy	• CBOB controls the CBDC issuance. • More effective management of inflation. • Enhance the forecasting capabilities. • Supports direct monetary interventions (i.e. natural disaster relief payments). • Transparency improved, however the overall impact on monetary goals is limited in a small, open economy. • Cash dependence among the population limits its effectiveness as a policy lever.	• CBN controls the CBDC issuance. • More effective management of inflation. • Enhance the forecasting capabilities. • Supports direct monetary interventions (i.e. welfare payments, tax payments), supporting fiscal management. • Reliance on cash limits scalability and policy impact, especially in inflationary regions. • Centralised supervision may raise trust issues.	• PBoC controls the CBDC issuance. • More effective management of inflation. • Enables real-time tracking of money flows and faster policy transmission. • Programmability supports targeted interventions, improving the liquidity management with conditional and programmable payments. • Presence of a digital ecosystem that increased the adoption rates. • Oversight concerns might impact the adoption rates.
Financial Stability	• Strengthen financial inclusion. • Decreases cash management costs. • Enhanced transaction security through blockchain. • Cash preference and digital illiteracy may slow widespread uptake. • High mobile penetration aids adoption, but infrastructure in remote areas might be a barrier.	• Focuses on the decrease of inflationary risk, reduction of informal economy and growth of government revenue. • Payment transparency aids anti-corruption efforts. • Supplements cash and existing electronic payments. • Power and internet issues affect availability and stability.	• Focuses on monetary sovereignty and reduces reliance on private tech companies for payments. • Centralised ledger and integration with banks enhance control and fraud prevention. • Cashless payments reduce cash management costs.

Dimension	Sand Dollar	eNaira	e-CNY
Legal Accountability	- Built into existing financial laws, with updates for digital currency. - Compliant to several regulations including AML/CTF, KYC, privacy, data confidentiality and consumer protection. - Integration with available banking systems. - Oversight focuses on financial inclusion.	- Amended Central Bank Act and the Banks and Other Financial Institutions Act to authorise digital currency. - Compliant to AML/CTF, KYC, with regulatory guidelines for all participants. - Data privacy covered by NDPR. - Consumer rights and dispute resolution mechanisms are robust. - Attention to informal economy issues.	- Amended PBoC Law to give digital currency equal legal status to cash. - The oversight model supports the digital governance agenda of the country. - Compliant to AML and CTF regulations, data protection. - Legal foundation enables innovation.
Transition Strategy	- Gradual, voluntary adoption with cash remaining the preferred mean of payment. - Gradual approach, users may choose between cash and digital currency. - Incremental rollout to avoid marginalising vulnerable groups. - Implementation reduces resistance and fears of surveillance.	- Parallel circulation with cash, prioritising user awareness and training. - Remittances facilitated by lower transaction fees. - Aims to reduce informal economy and boost transparency. - Trust and security concerns persist.	- Extensive pilot programs across the country. - the Banks and Other Financial Institutions Act to authorise digital currency. - Environment conducive to digital payments, with potential challenges for less tech-savvy users. - Part of broader economic modernisation and dual circulation plan.

Dimension	Sand Dollar	eNaira	e-CNY
Regulatory Oversight & Ethical Implications	• Tiered KYC system balances inclusion and compliance, with wallet levels based on identification. • Lower-tier wallets require minimal personal info, supporting accessibility and privacy for small transactions. • Strong AML/CTF compliance, but limited surveillance may impact regulatory reach. • Decentralised, prioritising user privacy and autonomy. • Model praised for safeguarding freedom.	• Tiered KYC for easy onboarding. • Intermediate centralisation, with focus on inclusion, consumer safety, and compliance. • Privacy and trust might need consolidation. • Regulatory framework adequate to support international operations. • Cautious approach to avoid over-regulation.	• Tiered KYC with 4 different wallet levels. • Multi-layered security architecture prioritises data management and oversight. • Centralised, with high compliance and oversight. • Privacy trade-offs for control and supervision. • Supports national security and social stability. • Strategic tool for monetary sovereignty and international influence.

Source: Author's elaboration.

B. DESIGN AND TECHNOLOGY REQUIREMENTS

3.1.6. MODERNISATION OF PAYMENT SYSTEMS

CBDCs may foster the efficiency of payments, reducing transaction costs and execution time of cross-border transactions (BIS et al., 2021a). Adrian and Mancini-Griffoli (2021b) concur that the digital transformation of payment systems leads to the diminution of transaction costs and to the execution of domestic and cross-border payments at a higher velocity.

The Bahamas decided to strengthen its financial independence and to modernise its banking system through the launch of its own CBDC, addressing several payment areas (Wright and Todd, 2024). The Sand Dollar represents an attempt to decrease dependence on physical cash, in case of natural catastrophes (Nguyen, 2024). The Bahamian government aims to position the Sand Dollar as a pioneer of financial innovation, possibly driving fintech investments, raising its international standing. The government's endorsement expresses an interest in the application of technology for national development. However, the Sand Dollar's impact on global finance and politics may be limited. By reducing the country's dependence on physical cash, the Sand Dollar may cut down the cost of processing, disseminating, transporting and protecting cash around the archipelago (CBOB, 2021d). It may also reduce the need for physical infrastructure, which is particularly valuable in places where natural disaster occurs. Research suggests that the Sand Dollar may increase transactional resilience with its Hyper Converged Infrastructure (HCI) designed with end-to-end encryption and two layers of secure data storage, including the DLT (Branch, Ward and Wright, 2023). The Sand Dollar is compatible with existing domestic payment networks. It is distributed with a dual mechanism, in which the CBDC is issued by the CBOB to the AFIs, which in turn distribute it to end-users (CBOB, 2019), although this may generate a dependency on the technical Infrastructure of the AFIs. The Sand Dollar wallets connect with existing financial institutions and payment service providers, funds can be easily transferred from digital wallets to bank accounts and vice versa (Nguyen, 2024). The Sand Dollar facilitates faster payments across the archipelago, it works through mobile technology and allows to reach the unbanked and underbanked groups of population, with wallet applications that run on smartphones (Bilgen, Dutto and Colberg, 2024). The Sand Dollar is expected to foster the resilience of the local economy in the Bahamas, by facilitating transactions and providing an alternative mean of payment (Branch et al., 2025).

The eNaira represents the government's efforts to modernise the payment systems and to reduce the informal economy (CBN, 2021a). The eNaira is connected to the existing banking

networks and it enables users to link digital wallets to their bank accounts (Chukwuere, 2021). Given the success of mobile money in Nigeria, the eNaira is compatible with mobile payment platforms and can be accessed via feature phones, through USSD technology (Idisi et al., 2024). The CBN has tiered levels of KYC that make user onboarding easy, ensuring regulatory compliance (CBN, 2021b). The eNaira makes use of existing merchant systems and financial agents to increase its adoption rate and to ensure interoperability (CBN, 2021a). The CBN is working to create cross-border interoperability for remittances and support the needs of the Nigeria's expat diaspora (Esoimeme, 2021). Insufficient public knowledge may have an impact on adoption and usage (Ogunrinde, 2023). Furthermore, low levels of financial and digital literacy influence the users' potential to make use of the eNaira (Ozili, 2023a). The support from the Nigerian government reflects an attempt to make use of innovative technologies for digital transformation purposes. The eNaira can execute different types of transactions from peer-to-peer payments to the purchase of services and goods, also enabling the receipt of government subsidies and grants. Allowing direct payments between users, the eNaira may reduce intermediaries and thus transactions costs, boosting efficiency. The CBN has made it convenient for suppliers to accept the eNaira through incentives and payment systems' integration.

By modernising the financial system, the e-CNY may make China's payment infrastructure more efficient and may reduce the dependence on private payment platforms (Li, 2024). Payments through e-CNY are accepted by thousands of merchants. In economic terms, the e-CNY aims to facilitate payments in a more efficient way, to alleviate cash dependence and to reduce the hegemony of private payment providers (Huang and Li, 2023). Additionally, it aims to support better monetary policy transmission strengthening the resilience of the financial system (Saliya, 2025). A mass adoption of the e-CNY may boost China's economy, by improving the efficiency of transactions and reducing associated costs (Caudevilla and Kim, 2022). In future, the use of sophisticated capabilities such as programmable money and smart contracts may enable automated payments, according to predetermined rules (Lyu et al., 2023). The e-CNY also promotes cross-border trade in pilot programs, enabling the future execution of international trades and tourism transactions through its platform (Radic et al., 2022; HKMA and PBoC, 2024). The implementation of international interoperability involves regulatory alignment and building trust at international level (Prasad, 2022).

Cover-Kus (2021) claim that CBDCs in small economies are mainly used to stabilise and modernise the domestic financial infrastructure. The Sand Dollar can illustrate how a CBDC can drive financial inclusion for a small economy, by leveraging mobile devices and by integrating existing banking platforms. The eNaira has modernised payments in Nigeria, amid

difficulties due to infrastructural issues. Cheng G. (2022) frames the e-CNY in the context of China's Digital Silk Road project, to promote China's economic development internationally. The e-CNY illustrates the challenge of adopting a CBDC in a vast advanced economy, competing with private payment services. The development and modernisation of cross-border payment systems have emerged as an important point of cooperation between international organisations, national monetary authorities, financial institutions and technology companies. Even though CBDCs can be a powerful tool that complements physical cash, digital currencies need to be carefully designed to modernise payments, striking the right balance between unlocking their potential and addressing concerns about privacy, security and accessibility.

3.1.7. SECURITY

Adequate cybersecurity measures are essential for preventing fraud and securing users' data (BIS, 2023g). Despite presenting several benefits, CBDCs can introduce new security threats. Contrarily to physical cash, CBDCs need secure and resilient infrastructure to withstand cyberattacks, to safeguard user data and to maintain transaction security, preventing other risks that might arise from the functioning of payment systems (Niroula et al., 2024). CBDC security features can reflect the cyber readiness of a country, and may depend on the national digital infrastructure, financial regulatory framework, and political objectives (BIS and SNB, 2023). High encryption protocols should be implemented to secure transactions and to protect users' data. Advanced Encryption Standards (AES) may be implemented to protect integrity of data and privacy. The wallet may store cryptographic keys inside the devices, utilising secure components. Secure Socket Layer (SSL) encryption may be used to transmit data between users and the financial intermediaries. All three CBDCs offer advanced security features, to safeguard users from fraud such as encryption and multi-factor authentication.

As the world's first CBDC, the Sand Dollar utilises a DLT-based infrastructure with an equilibrium of accessibility and safety (Branch, Ward and Wright, 2023). The Bahamas' emphasis on the security aspects of the Sand Dollar relies on its DLT technology, which adopts some built-in security measures, including transaction immutability, transparency, and fraud prevention (Rolle, 2019a). Its architecture uses DLT for decentralisation and audit, helping to prevent dangers such as unauthorised access and counterfeit risks, providing a safe environment (Branch, Ward and Wright, 2023). The Sand Dollar is designed for safety, the authentication mechanism includes secure login credentials and biometric verification (CBOB, 2019). The Sand Dollar encrypt transactions end-to-end and supports multi-factor authentication, through PIN, and biometric solutions (Bilgen, Dutto and Colberg, 2024). Stored

data conforms to the Data Protection Act (Privacy of Personal Information), keeping user data secure from unauthorised access (CBOB, 2021d). The Sand Dollar contributes positively to financial inclusion by being accessible through mobile phones, commonly available in rural areas (Colebrook, 2022). The tiered KYC model provides accessibility and security, allowing users with limited identification documents, to engage in the digital economy, within acceptable transaction thresholds (CBOB, 2019). Given the country's relatively limited technological infrastructure, the Sand Dollar has adopted a simplified system of digital identity verification that relies on partnerships with local banks for KYC compliance (Bilgen, Dutto and Colberg, 2024). This model, though highly effective for the Bahamas, might not be supportive of future scalability, in an evolving technological environment. Furthermore, while this model allows for financial inclusion, the dependence on financial intermediaries can pose risks. The Sand Dollar's security approach relies on the resilience of the AFIs, which might create pitfalls, if these companies are subject to cyber-threats. If authorised intermediaries would be compromised, then this would have a detrimental effect on the overall security of the system. Sisodia (2024) found that the simplified DLT architecture used by the Sand Dollar may experience limitations, enabling partial scalability, with constantly growing cybersecurity requirements. Additionally, Branch, Ward and Wright (2023) maintain that the security of the Sand Dollar may be suited to the Bahamas' size, however, it might be threatened by increased transaction volumes and potential cybersecurity concerns. The CBOB (2020b) controls and monitors the AML and CTF compliance for the Sand Dollar, a very important mechanism for this CBDC. AFIs are accountable for tracing payments and for informing the Financial Intelligence Unit (FIU) of suspicious transactions. The CBOB performs supervision and ensure that AFIs would meet regulatory requirements (CBOB, 2021d). The CBOB has mandated security controls, such as requiring multi-factor authentication for all users and introduced standards for AFIs (Branch, Ward and Wright, 2023). This has increased adoption rates, with more than 113,000 consumer wallets paying with Sand Dollars in 2023 (CBOB, 2023d). There were efforts towards improving user awareness of security best practices and in expanding the AFI network to additional entities (CBOB, 2023c). For the Sand Dollar ecosystem, the simplified blockchain may pose risks in response to larger transaction volumes and potential cybersecurity concerns.

The Nigeria's eNaira prioritises security in a more complex architecture, with a bid to enhance financial inclusion, through a mobile-first digital currency (Samuel-Ogbu, 2022). The eNaira has embraced a security architecture that considers the country's infrastructural constraints. The CBN has built a security setup to protect the eNaira ecosystem against cyber security risks (CBN, 2021a). The eNaira was developed on a permissioned blockchain, operated by the CBN, guaranteeing transparency, immutability, and security (Idisi et al., 2024). The

blockchain system provides tamper-proof transaction signatures, removing the possibility of single points of failure (CBN, 2021a). Akindipe, Akhimie and Olonade (2023) points to the eNaira's ability to transform Nigeria's financial industry, but he also highlights cybersecurity concerns. The eNaira is protected through encryption algorithms and secure login systems that safeguard the privacy of users' information. The eNaira offers various security measures including mobile biometric authentication, PIN, OTP authentication, and USSD codes for feature phone users (CBN, 2023b; CBN 2023i). These characteristics enable a safe connectivity, which is of utmost importance to gain consumer trust (Suoye, Nnaemeka, and Itotenaan, 2022). The CBN has put in place advanced cybersecurity measures, such as intrusion detection, strong internal control measures, and regular IT security assessments (CBN, 2021a). The cybersecurity measures were deployed to defend against cyber-attacks, also in consideration of potential phishing attacks targeting eNaira account holders. Coordination with cybersecurity suppliers and continuous education campaigns may be beneficial for the eNaira. Similarly to the Sand Dollar, the eNaira uses a tiered KYC with different degrees of user identification (CBN, 2021a). This methodology allows for the inclusion of unbanked users without hampering regulatory controls. Higher transaction limits and additional services are provided to users who are fully identified by the CBN. Similarly to the Sand Dollar, while the reliance to authorised financial intermediaries can support financial inclusion for Nigeria, however, it might introduce dependencies and potential cyber-threats, if one of the partner institutions would be compromised by cyber threats. User education initiatives and infrastructure improvements are planned to develop its security (CBN, 2021a). The CBN has focused on expanding the adoption of the eNaira through partnerships with fintech and mobile network operators to enhance accessibility, and to improve awareness through dedicated campaigns on safe usage (CBN, 2023a).

The PBoC has prioritised the implementation of robust cybersecurity measures against fraud and hacking, in consideration of the risks entailed by the volumes transacted by the e-CNY (Mu, 2023). The e-CNY uses an advanced, multi-layered security framework that reflects China's focus on digital sovereignty and advanced data management. This approach represents a balance between scalability and control, it enhances central bank monitoring on the economy, however it raises concerns over surveillance and data privacy for users. According to Mu (2023) and Cheng P. (2022), the e-CNY's dual offline wallet system provides secure device-to-device payments, without access to the internet, using NFC technology and encrypted secure hardware in devices, particularly helpful for isolated areas. This capability is crucial to support China's rural regions, where internet connectivity can be limited, and to allow for inclusive digital payments. In terms of security, the offline capability makes transactions more reliable, less subject to centralised servers and less vulnerable to cyberattacks.

However, the dual offline payment may be subject to dedicated standards, to avoid potential transaction reconciliation issues and fraud risks (Huang and Li, 2023). Subrahmanyam (2023) report that offline transactions might potentially involve machine-to-machine payments, with e-CNY wallets used across internet of things devices, for instance in home appliances or in vehicle sensors. The e-CNY architecture enables regulatory oversight on transactions, with potential conflicts on personal privacy (Fanusie and Jin, 2021). The e-CNY offers industry-leading security to ensure the safety of users' money and information. The authentication is performed through passwords and biometric identification. Hardware wallets were also tested for more convenience (PBoC, 2021). In tiered wallets system, user identification, transaction caps, and levels of anonymity are tied to each other (PBoC, 2021). The e-CNY uses controllable anonymity to strike a balance between data privacy for users and regulatory compliance (Cheng P., 2022). Users can conduct low amount transactions anonymously, but the PBoC maintain access to data for the prevention of criminal activities and the traceability of transactions for regulatory compliance purposes (Cheng P., 2022). The e-CNY is secured by cutting edge cryptographic algorithms to prevent fraud. Payments are encrypted to avoid cyber threats (Fullerton and Morgan, 2022). The e-CNY uses public and private key encryption, digital signatures and encrypted hash algorithms for securing payments and authenticating transactions (Kuvaeva, Chudinovskikh and Sedunova, 2021). The PBoC has authority over key management, performs monitoring activities and can intervene as required in the process. The integration with the existing payment systems, as well as extensive pilots in multiple cities are indicators of the scalability and robustness of the e-CNY (Li, 2024). Security improvements involve strengthening the resilience of the dual offline payment mechanism and fine-tuning of the controllable anonymity mechanism (Mu, 2023).

The security features among the analysed CBDCs reflect the strategic, technological, and economic priorities of each country. The Sand Dollar's lightweight model focuses on accessibility and financial inclusion, although it might experience potential issues with the scalability and robustness for future growth (Bilgen, Dutto and Colberg, 2024). The eNaira combines the convenience and security provided by biometric authentication in a limited infrastructure context but might introduce mobile network concerns. By contrast, the e-CNY is a centralised, advanced platform, aligning with China's priorities (Xia, Gao and Zhang, 2023). The security architecture of the Sand Dollar, the eNaira, and the e-CNY illustrate different ways to balance safety, privacy, and inclusivity within CBDCs. While the Sand Dollar's focus is on usability through a simplified security architecture, the e-CNY and eNaira are built with more robust security systems that are tailored to their larger, more complex infrastructures. The three case studies demonstrate how security can complement national priorities, and that the implementation path of CBDCs may need to be carefully navigated both technically and

socially. Cybersecurity is a permanent concern for digital currencies, as the trust in the platform is dependent upon the CBDCs' resilience against hacking, fraud and technical outages. Future investments in regulatory compliance and cybersecurity should be prioritised.

3.1.8. SCALABILITY

The scalability refers to the ability of a CBDC platform to scale up, responding to a rise in transaction volumes, and to meet the demand of an increasing number of users. This represents a significant element for the sustainability of digital currencies in the long term. CBDC systems should be able to expand, without disrupting core operations, to keep up with business demands.

The Sand Dollar is designed for domestic volumes of transactions, suitable for the population of the Bahamas (CBOB, 2019). The platform is reasonably stable for the current use, and it might require enhancements to process higher transaction volumes. Infrastructural upgrades would be probably required to handle greater traffic, if the Sand Dollar would be adopted in the wider Caribbean area. The Sand Dollar's platform is particularly suitable for smaller, economically diverse environments. The DLT type of infrastructure is resilient and flexible, but it is more expensive and process transactions at slower speeds when compared to centralised solutions (Schär, 2021). The decentralised mechanism facilitates the Sand Dollar's mission of financial inclusion in the Bahamas, but it poses questions on whether it can scale successfully to sustain increases in transaction volumes (Sisodia, 2024). The Bahamas took a hybrid approach that combines central management with decentralised components to support regional scalability, but it might be constrained by limitations of its open economy (Cover-Kus, 2021). The Sand Dollar's objectives to provide financial services to the underserved groups of populations in rural areas of the Bahamas, might be hampered by a reduced scalability, due to the absence of digital infrastructure in these areas (Branch et al., 2025). The Sand Dollar's DLT technology enables modular upgrades, allowing the CBOB to adjust when requirements for scalability might change (Branch et al., 2025). On the other hand, the Sand Dollar, has potential cost issues, due to its infrastructure that may require additional resources to process high volumes of transactions (Branch et al., 2025). The Sand Dollar has the potential to grow in the Caribbean Community (CARICOM), to support financial integration across the region. The Sand Dollar's privacy protocol is aligned with CARICOM standards (CBOB, 2021d).

With Nigeria's emphasis on the domestic market for the eNaira, the ambitions for the scalability may be in-country and for the remittance payment corridors (Chukwuere, 2021). The eNaira present a hybrid combination of DLT elements, and it is designed to manage scalability

considering the local infrastructure constraints. The hybrid architecture of the eNaira offers flexibility, but continuous upgrades may be required to scale the platform, hinting that further investment may be needed to sustain the growth (Ozili, 2023c). Nigerian authorities continue developing the eNaira support infrastructure; however, studies show Nigerian ICT infrastructure as potential limitation to scale the eNaira, in case of a surge in transaction volumes (Idisi et al., 2024). The eNaira may have moderate costs of ownership, however its scalability might be limited by infrastructural constraints, although the currency may still have the potential to achieve its assigned objectives (Chukwuere, 2021). Furthermore, the availability of digital devices and intermittent internet connectivity in rural areas of Nigeria may represent important constraints for the users' groups (CBN, 2023a). Research has shown that while eNaira can process high volumes of transactions, the low digital literacy levels among the population and intermittent connectivity in rural areas could slow down the adoption (Obiora, 2023a). While blockchain provides built-in security, the scalability of the eNaira may be impacted by infrastructural gaps and limited user awareness (Ogunrinde, 2023). Improvements in network capacity and educational campaigns by the CBN were implemented, to strengthen user adoption (CBN, 2023h).

The PBoC designed the e-CNY as a hybrid platform, to support the efficient processing of payments and adequate execution speed. The e-CNY enjoys advanced security protocols, and it ensures interoperability with China's largest payment platforms, with a specific focus on scalability (Branch et al., 2025). The platform is optimised for China's vast transaction volumes. Studies have shown that centralised solutions can speed up operations, guarantee lower latency and provide control over transactional data (Zheng, 2023). Thanks to China's extensive fintech infrastructure investment, the e-CNY's high-capacity system can process millions of transactions (Cheng P., 2022). This capability ensures operational excellence in urban areas but may be affected in rural areas with limited connectivity. Recent pilot programs in Shenzhen, Suzhou, Chengdu, and Xiongan, have proven that the e-CNY can scale to large urban transactional requirements, but rural areas may call for further expansion of the infrastructure, to achieve country-wide scalability (Kshetri, 2022). The e-CNY is supported by China's investment in digital infrastructure, allowing for rapid scalability and integration with other technological innovations. The government's support for the e-CNY places it among the most scalable solutions of the CBDCs analysed, from an implementation and maintenance perspective. The e-CNY could scale rapidly in China's densely connected economy, especially in urban and semi-urban markets, but it may require incentives to gain acceptance in rural isolated regions.

The Sand Dollar's scalability limitations may be explained by the infrastructural constraints in small economies, which can create problems if payment volumes increase (Sisodia, 2024). The eNaira's system architecture heavily relies on Nigerian ICT infrastructure, which might impact on its scalability. The e-CNY combines a centralised payment engine, with robust technology to manage transactions volumes suitable for a major economy (Saliya, 2025). The e-CNY's platform is engineered to process a high number of daily transactions across millions of users, with strong security (Cheng P., 2022). Investments in technology, security and privacy will continue to be necessary to ensure the scalability for all the three CBDCs analysed, in line with increasing adoption rates.

3.1.9. USER EXPERIENCE

The User Interfaces (UI) of CBDCs represent an important element for the user adoption, and for the attainment of policy objectives related to financial inclusion, digital sovereignty, and consumer protection. An appealing UI can reduce the barriers between difficult technical infrastructures and user-friendly applications, increasing adoption rates.

The Sand Dollar puts simplicity at the centre of its development, emphasising its usability to ensure adoption across all age categories and eliminating barriers to entry. Wright et al. (2022) argues that Sand Dollar's simple design plays a role in the product's ability to support financial inclusion. The UI is minimal, omitting advanced functionalities to make it easily accessible. It offers multilingual solutions for local dialects, which is important for serving a range of Bahamian communities. It's easy to use for those with a limited connection, it supports offline payment and places emphasis on inclusion for marginalised groups (CBOB, 2019). The application can be downloaded from the Apple Store and from Google Play, it is possible to observe it directly, its UI is simple, and its navigation and visual cues are targeted towards those who are not familiar with digital finance. Its UI provides minimalism to users of digital banking services, supporting financial inclusion with a straightforward and simple interface. The Sand Dollar's offline feature allows the users in remote locations to conduct transactions without access to the internet, making it more accessible (CBOB, 2020c). The CBOB shows that the offline capabilities can be utilised in areas where the network is not stable (CBOB, 2019). As Kim and Mohan (2020) argue that the UI enables end-user accessibility. The UI is both secure and privacy friendly, with data protection layers following Bahamian privacy standards (CBOB, 2021d). Its design conforms with privacy laws and regulations, as the data protection features are compliant with local regulations, to ensure security and privacy. It is built to be interoperable with mobile wallets and bank systems, and users can directly connect their bank accounts (Sisodia, 2024). The UI has the potential to increase financial inclusion

and economic participation in small open economies, supporting national economic growth (Wright and Todd, 2024). The interface is minimal, with a basic icon set and a straightforward language, appealing to people with diverse digital literacy levels. The onboarding is easy with users required to input only a small amount of data to open an account, reducing barriers to entry. Moreover, the accessibility functions have been equipped with adjustable font size and voice-assistance functions that have been built into the design to aid the elderly and the disabled.

The eNaira mobile app is designed in a minimalistic style, with large icons, simple instructions and self-guided support tutorials for all levels of users. The application can be downloaded from the Apple Store and from Google Play, it is possible to observe it directly. The wallet applications have an organised interface and basic features such as money transfer, history viewing, and account settings (CBN, 2021a). It's functional and intuitive, although the initial versions of the app that were criticised for usability shortcomings, technical issues, slowness, and inconsistent navigation, were fixed incrementally (Idisi et al., 2024). The UI is user-friendly and can be promptly adopted by people lacking digital literacy. It integrates with bank accounts and mobile wallets. Research reports show that the deployment of the eNaira in rural areas is key for a successful adoption (Adedipe, 2022). The interface has sophisticated security features to ensure data protection, including biometric authentication (CBN, 2023i). Its UI aims at inclusivity, by increasing adoption and usage of digital financial services for rural, unbanked communities in priority demographics, as part of Nigeria's overall economic development (CBN, 2022). The eNaira has privacy protections and offline features embedded to encourage financial inclusion. Ozili (2023a) notes that digital literacy might represent a concern among users. Recent research has shown that user education initiatives may be needed in low-literacy areas, to drive adoption rates and to achieve the inclusivity targets (Akpan and Umaru, 2024). With its simple interface, effective tutorials and help desk services, the eNaira put emphasis on usability in a country with low digital literacy (CBN, 2021a). The eNaira's UI focuses on easy navigation, offline use, and support to assist those with low levels of digital literacy, in line with Nigeria's development priorities (Akindipe, Akhimie and Olonade, 2022). Ozili (2023a) explains how the eNaira can improve transparency in Nigeria's informal economy, however the challenges, due to the low levels of digital literacy, may significantly limit its impact. The UI layout, the type of information collected, and the authorisation mechanism implemented may influence user adoption. The CBN has issued upgrades to the eNaira app, to address bugs, improve usability, enhance performance and user experience, with the goal to expand the adoption rates. With security improvements, easier registration, multilingual support and visual aids, the new product is designed to fit into Nigeria's multilingual society (Idisi et al., 2024). To encourage usage, the CBN has introduced incentives

including discounts on using the eNaira at approved merchants and a reduction in transaction fees (Idisi et al., 2024). The CBN has also begun to build partnerships with fintech startups to develop solutions that could integrate with the eNaira platform.

The e-CNY UI is architected with high-end digital sophistication, focusing on urban and digitally connected individuals, but also addressing the rural-urban digital divide (Gu, 2023). The e-CNY application can be downloaded from the Apple Store and from Google Play but can only be accessed if the position of the phone is in one of the areas, where the e-CNY pilot project is active, at the time of writing, in 29 cities (Huang, 2025). Thanks to the Chinese advanced digital infrastructure and high penetration of mobile phones, the e-CNY UI puts special emphasis on innovative features and connectivity with established financial technology ecosystems (Li and Huang, 2021). The UI is visually stimulating, intuitive with the inclusion of voice recognition and facial recognition and with interactive elements. It offers advanced functions such as voice commands, QR code payments, and integration with popular payment apps. The e-CNY app comes with advanced features such as facial authentication and *touch and go* NFC payments (Xu J., 2022). The UI structure has important components that reassure users about its security. While the innovative features may be beneficial for users, they can also complicate matters and turn away people unfamiliar with digital finance, older age groups or residents in rural areas where digital literacy is limited (Chin, 2025). The app is integrated with Chinese digital payment platforms such as Alipay and WeChat, to promote user adoption with a focus on economic growth, through the digital domain (Xu and Jin, 2025). This integration, however, can perpetuate the urban-rural division, due to entry barriers imposed by the low digital literacy levels (Kuvaeva, Chudinovskikh and Sedunova, 2021). Prasad (2022) maintains that the e-CNY's advanced features might have an impact on less technologically aware groups of the population. Furthermore, its UI design, albeit unique, does not offer a proper solution to China's digital divide and may not fulfil the CBDC's objectives of inclusivity. The PBoC has introduced simplified functionalities within the app and educational resources to assist users (Mu, 2023). Among the new UI elements there are programmable money features (allowing users to define payment conditions) and compatibility with public services (Huang, 2025).

The CBDCs' UI design plays a crucial role in ensuring user acceptance, effectiveness, and compliance with national economic and political targets. The Sand Dollar's focus on simplicity and accessibility is consistent with the Bahamas' goal of financial inclusion and shows the alignment with the local community requirements. Digital literacy barriers may impact the eNaira's balance between functionality and ease of use. The e-CNY's advanced UI supports China's desire for modernisation and compliance. The study demonstrates how technology

choices affect both economic goals and political objectives. By providing alternatives to circumvent the technology limitations in developing economies, and by tailoring their solution to the socioeconomic and political realities of the deployment regions, the UI designs may be able to maximise the utility and accessibility of CBDCs.

3.1.10. TECHNOLOGY REQUIREMENTS

The technical infrastructure represents a key component for the CBDCs' interoperability, and it is an enabler for the digital currencies' ecosystem and user growth. For example, the technical infrastructure is influenced by the quality of the internet connectivity, mobile penetration and cybersecurity posture and it directly determines how CBDCs can be efficiently deployed and scaled (BIS et al., 2021a). Privacy requires complex encryption algorithms and data-storage technologies (Auer and Böhme, 2020). The implementation of centralised or decentralised ledger technology may have implications for privacy and system resilience, and a direct impact on CBDCs' scalability. The Sand Dollar and eNaira, respectively, are DLT based and security-driven (CBOB, 2019; CBN, 2021a). China presented a technological landscape favourable for the integration of its CBDC in the digital economy. The digital ecosystem in China has helped to facilitate the e-CNY implementation (Cheng P., 2022).

The Sand Dollar adopts a permissioned DLT system, combining decentralised storage and user-level encryption to provide adequate privacy protection. It utilises a low energy, Hyper Converged Infrastructure (HCI), with end-to-end encryption and two layers of secure data storage, including the DLT (Branch, Ward and Wright, 2023). The Sand Dollar use a secured digital platform, i.e. a permissioned DLT, specifically the NZIA Cortex DLT, provided by NZIA Limited (later rebranded as Movmint), and owned by the CBOB, for robustness and accessibility, with DLT technology providing transaction security, transparency, integrity and resilience (Atlantic Council, 2025). The system is designed to operate offline, and transactions can be carried out without access to internet, making it able to work in the Bahamas' rural communities with low internet penetration. The low-bandwidth network requirement is consistent with the Bahamas' limits for infrastructure-demanding products (Kim and Mohan, 2020). The platform integrates with existing bank networks and payment institutions. The Sand Dollar mobile wallet is accessible via mobile app for smartphones, feature phones, and physical cards, making it more appealing to different age groups (Nguyen, 2024). Its scalability might be challenging, as the DLT component might not be able to support high transactional volumes, as usage increases (Sisodia, 2024). The Sand Dollar's reliance on mobile technology also highlights the importance of having stable internet access. In the Bahamas, with high mobile penetration and intermittent internet connectivity on many of the islands, the

availability of the Sand Dollar's digital wallets through smartphones represents a safe and flexible option for users (Sisodia, 2024). Its design also helps to make the wallets accessible without requiring continuous connectivity, which is especially important in a geographically distributed country (CBOB, 2022). The Sand Dollar distribution requires robust cybersecurity procedures to prevent potential data breaches, with investments in technology that might be required to sustain the long-term growth. Its UI interface is designed to support users regardless of their level of technology skills (Wright et al., 2022). Notwithstanding its positive contribution, obstacles remain for the achievement of the Sand Dollar's full potential, including the fact that many remote communities continue to experience sporadic power and internet availability, in areas without reliable supply (Branch et al., 2025). Other authors have favoured the ability of the Sand Dollar to maintain technological resilience, suggesting that it could become an important alternative payment system in case of natural disasters (Rolle, 2019b).

The CBN created the eNaira in collaboration with fintech company Bitt Inc, through the Hyperledger Fabric private DLT, which efficiently manages energy requirements. (Atlantic Council, 2025). The eNaira utilises a DLT, to protect transparency along with security and transaction immutability, while enabling programmability capabilities (CBN, 2021a). The Hyperledger Fabric platform was selected because of its permissioned network capabilities, giving the CBN control over transactions' validation. The platform is interoperable with existing bank systems and allows transactions of different nature, such as peer-to-peer, merchant, and foreign remittances. The eNaira supports offline access, although Nigeria's limited technical infrastructure challenges the stability of access (Idisi et al., 2024). The eNaira provides adequate options for accessibility, with a mobile app for smartphone and USSD codes for feature phones (CBN, 2023b). The two-tier distribution model of the eNaira is dependent upon financial intermediaries, however constraints related to the technical infrastructure and low digital literacy in Nigeria may delay the users' base and transactional volume growth (Chukwuere, 2021). The eNaira's reliance on central bank-provided digital wallets may face constraints, in parts of the country with low digital literacy levels and poor technical infrastructure. Continual investment in technology infrastructure, along with user training programs may support the long-term viability of the eNaira. The eNaira's architecture is designed for accessibility, analysts argue that it does enable direct welfare interventions for the population, furthermore, several infrastructure-related problems, including inconsistent power supply, irregular Internet access and low smartphone ownership in rural communities, may have an impact on the adoption of the eNaira (Suoye, Nnaemeka, and Itotenaan 2022).

The e-CNY uses a hybrid platform, which combines distributed and platform-based technologies, with multi-layer security, which runs on a multi-site, high availability infrastructure

capable of guaranteeing business continuity and 24/7 services (PBoC, 2021). This platform provides transaction efficiencies and scalability, to meet the vast volume of transactions that is appropriate for the Chinese economy (Sun, 2021). Distributed technologies are in part deployed to ensure transaction security and openness, while remaining centralised (Jiang and Karman, 2023). Its core engine runs on a centralised network, owned by the PBoC, which eliminate the requirement for the energy-intensive mining or computational power needed by cryptocurrencies, thus making CDBC more energy efficient. The PBoC provides centralised issuance and validation of the e-CNY, with distribution and user interfaces managed by traditional banks and payment providers for greater security and efficiency. The e-CNY implemented secure hardware, encryption and cutting-edge technologies, such as biometrics (Xia, Gao and Zhang, 2023). Its advanced platform allows transactions' monitoring to prevent financial crime. The e-CNY uses sophisticated technologies such as dual offline payments, to execute transactions without access to the internet (PBoC, 2021). The e-CNY is integrated with the existing payment systems, performs QR code payments, support NFC technology, which enhance accessibility but might pose risks related to the interoperability (Saliya, 2025). The e-CNY's adoption rate in China's high-tech economy demonstrates how valuable technological solutions can foster acceptance (Ledger Insights, 2024c). China's advanced digital infrastructure, combined with government investments in cybersecurity, enabled the e-CNY to establish secure connections with traditional banks and payment service providers. Digital wallets of the e-CNY interface with leading payment services, like Alipay and WeChat Pay. According to Mu (2022), the e-CNY's two-tier architecture is an effective way to improve transaction monitoring transparency, the system is designed to incorporate data privacy protection for users, and the e-CNY is easy to integrate with the digital infrastructure, such as digital wallets, that consumers already use. The e-CNY depends on sophisticated tech and requires ongoing investment in cybersecurity and system robustness to scale with increased transaction volumes.

There are varying degrees of technological solutions and capabilities among the three CBDCs. The Bahamas and Nigeria experience infrastructural limitations like intermittent internet connectivity and low levels of digital literacy among the population (World Bank, 2025a). The CBOB has designed the Sand Dollar to operate on smartphones and to support offline functionalities to ensure resilience (CBOB, 2019). Researchers commended the Sand Dollar's accessibility, which provides an alternative for payment to rural communities, without eliminating the supply of cash (Sisodia, 2024). Nigeria may prioritise the solution of issues such as infrastructural constraints, power failure and modest internet penetration in rural areas (World Bank, 2024). Such issues require the availability of offline payment solutions and collaboration with mobile service providers to expand coverage. The e-CNY benefits from

China's advanced digital infrastructure. China's modern society, with wide smartphone adoption, and people's familiarity with digital payments make it a suitable candidate for a CBDC deployment.

3.1.11. INTEROPERABILITY WITH EXISTING PAYMENT SYSTEMS

In CBDCs, the interoperability refers to the possibility that digital currencies may be transferred across multiple payment channels such as traditional banks, mobile payment apps, and international payment platforms. The integration of CBDCs with existing financial systems enables a straightforward interoperability, ensuring wide adoption and maximum utility, and it can substantially reduce transaction fees and improve the payment execution time. The controls adopted may have repercussion on cross-border interoperability, particularly with other CBDCs (BIS et al., 2021a). The Sand Dollar's integration with mobile wallets, for example, has the potential to enable low-cost, instantaneous payments that are available to both consumers and merchants. The e-CNY's integration with existing payment networks enables faster transactions and greater efficiency in a digitally intensive economy.

The Sand Dollar wallets can be integrated with traditional bank accounts, enabling users to associate their wallets with their bank accounts, to seamlessly transfer funds (CBOB, 2019). This close integration ensures the interoperability with the existing banking infrastructure. The Sand Dollar makes use of mobile technology to reach users across the islands, its digital wallet is compatible with smartphones and basic phones, to improve accessibility (Branch, Ward and Wright, 2023). The Sand Dollar is intended for use in everyday transactions, and in peer-to-peer transfers, it support transactions through QR codes, enabling a seamless shopping experience at retailers (CBOB, 2023g). However, the Sand Dollar does currently not support transactions through NFC technology. Alliances with local merchants and government institutions further developed the ecosystem, so that bills, salaries, and government subsidies can be paid through the CBDC. Merchants can accept the Sand Dollar through their existing POS systems to promote widespread adoption (Branch et al., 2023). Its platform complies with KYC and AML controls in accordance with current laws, to ensure financial integrity (CBOB, 2021d). Among the barriers to full interoperability, there are the areas identified by the CBOB for improvements which include the enhancement of the technical infrastructure, and the creation of awareness campaigns, to develop the low digital literacy (CBOB, 2023f). Wenker (2022) argue that the Sand Dollar is a positive solution, to foster financial inclusion through interoperability. The Sand Dollar has made financial services accessible in areas with low population density, by integrating mobile technology with existing financial institutions. The

Sand Dollar conforms to regional CARICOM privacy standards, helping to ensure regional scalability, among privacy-sensitive Caribbean users (Wenker, 2022).

The eNaira integrates its mobile wallets with existing bank accounts, supporting account-to-account transfers (Ozili et al., 2023c). The eNaira allows merchants to accept payments through existing point-of-sale applications, this integration is designed to foster widespread merchant adoption (CBN, 2021a). Since Nigeria has a significant component of payments executed through mobile money applications, the eNaira was developed to be compatible with mobile money providers (Sadat and Shaba, 2025). Integration with global payment systems is a strategic priority, as Nigeria has a considerable number of citizens living abroad. In fact, the eNaira is designed to process international remittances at lower rates and faster speed (Idisi et al., 2024). The eNaira Enables payment through QR and NFC technology. The Nigeria's intermittent internet connectivity and smartphone penetration might hinder the integration with digital payment platforms (Ozili et al., 2023b). CBN (2021a) stresses the importance of user experience. Suoye, Nnaemeka, and Itotenaan (2022) believe that the eNaira have legitimate ambitions but inform that technical and awareness issues may delay the realisation of the interoperability benefits. The technology solution of the eNaira may be adequate to provide confidence, through transparency, security, and customer service.

In China, the e-CNY brings competition to private payment systems, with the aim to reduce costs and to foster innovation (Wang, 2021). Its two-tier distribution model utilises existing bank infrastructure for distribution and customer support. The e-CNY is NFC compatible and can make payments through QR codes and also offline (Li, 2024). This feature provides greater interoperability in limited connectivity zones. China is involved in the Multiple CBDC Bridge (m-CBDC Bridge) initiative with the BIS Innovation Hub, and national monetary authorities from the UAE, Thailand, and Hong Kong (BIS, 2023f). This initiative explores interoperability in cross-border payments across CBDCs to reduce time and transaction fees. The PBoC has also initiated a collaboration with the Hong Kong Monetary Authority for piloting the e-CNY in Hong Kong (HKMA and PBoC, 2024). The e-CNY has advanced functionalities, such as the programmability that allows conditional payments (Mu, 2023). The e-CNY supports offline transactions and can be interoperable with wearable and IoT devices, further broadening its interoperability capabilities (Subrahmanyam, 2023). The structure of the e-CNY enables effective regulatory oversight to allow the PBoC to control the circulation of the currency, modulating scalability to national standards. To ensure broad global adoption, the solution of the regulatory and interoperability issues and more collaboration efforts will be required.

The interoperability is important for both the Sand Dollar and the eNaira to enable financial inclusion and to reduce transaction costs (Nguyen, 2024; Idisi et al., 2024). The Sand Dollar is powered by a secure, scalable platform designed for small open economies (Wright and Todd, 2024). The Sand Dollar demonstrates the potential of interoperability to drive financial inclusion in small economies with dispersed populations. The eNaira reflects how economies may leverage CBDCs to transform their banking infrastructure, despite infrastructural and awareness limitations (Ozili, 2023c). In China, the e-CNY interoperability is designed to boost competition in the payment system and to lower the dependency on private payment service providers (Branch et al., 2025). China's e-CNY is an example of the integration of a CBDC into an advanced and highly competitive payment system. China's digitally mature infrastructure underpins the international deployment of the e-CNY (Gu, 2023). CBDC adoption requires compatibility with existing payment systems to succeed. Technological solutions must be implemented to address barriers alongside establishing security measures to build public trust for successful interoperability.

3.1.12. PROGRAMMABILITY

CBDCs' programmability is the capability to insert conditional logic into digital money payments and is arguably one of the most important aspects that differentiate CBDCs from cash (Auer and Böhme, 2021). It allows central banks to impose sophisticated monetary policies, to automate complex payment transactions, to have accurate control of the circulation and usage of the currency and solve specific use cases (Cong and He, 2018). CBDC programmability may allow central banks to define sector-specific monetary allocation, expiry dates for funds, and conditional transfers (Auer and Böhme, 2021). Programmability may introduce technology risks in cybersecurity and scalability issues, which can vary across countries.

The Sand Dollar has two main goals, financial inclusivity, and resiliency to natural disasters (CBOB, 2019). Due to the Bahamian economy's dependence on tourism and seasonal jobs, the CBOB created the Sand Dollar to become a stable and easily accessible digital currency. Its primary scopes are to enable simple peer-to-peer transfers and to increase the efficiency of payments, rather than to elaborate programmable functionalities (Branch, Ward and Wright, 2023). The Sand Dollar has, in fact, limited programmability, making it difficult to introduce innovative monetary policy instruments (Wenker, 2022). For instance, in case of natural disaster, the Bahamian government might send programmable transfers to the areas involved, and resident might be able to access funds quickly (Rolle, 2019b). This programmable feature may allow rapid relief payments without intermediaries, demonstrating an unusual application

of programmability in emergency situations. Although programmability is limited, some researchers maintain that its initial design is still relevant for the country. Wright and Todd (2022) argue that the Sand Dollar's architecture strikes a balance between transparency and anonymity, while allowing for conditional controls on transactions, without sacrificing the decentralised platform of the Sand Dollar. Other authors point out that simple programmability enables adoption in a faster time frame, which is an important aspect for the Bahamas' situation (Nguyen, 2024). This was partly because the CBOB aimed to create a simple digital currency that could easily integrate with the existing financial system and be adopted by the public and private sector. Bilgen, Dutto and Colberg (2024) stated that, without sophisticated programmability, the Sand Dollar might not be suitable to perform advanced payment functions.

The CBN has expressed willingness to use the programmability for efficient allocation of welfare funds, which is expected to curb fraudulent activity on the social welfare systems (CBN, 2021a). The programmability of the eNaira is still in its early stages but has scope to expand to cover conditional cash transfers, government subsidy schemes and elimination of cash-based transactions. The eNaira is used to provide economic aid, which may be automatically vehiculated to authorised products and services, an example is represented by the Agro eNaira Wallet engagement launched by the CBN in 2023 (CBN, 2023c). Providing the flexibility to allocate subsidies to specific endpoints, may optimise the distribution of the benefits, restricting them only to their intended recipients. The eNaira could automate deductions of taxes at the point of sale and increase tax compliance and efficiency. Suoye, Nnaemeka, and Itotenaan (2022) point out that the eNaira may foster financial inclusion through direct welfare distribution. However, a cautious approach might limit the effectiveness of the eNaira for solving structural economic problems. Greater programmability could help the eNaira to address certain economic issues more directly, like delivering subsidies effectively, avoiding fraud or program allocation errors.

The e-CNY offers a good level of programmability, which is relevant to China's socio-political and economic development plans (Mu, 2023). The e-CNY may allow smart contracts to automatically impose conditional rules, such as fund expiry dates and conditional payments (Mu, 2023). The PBoC might be able, in future, to run policies such as interest rates and consumption subsidies, with potential impacts on spending habits (Yang and Zhou, 2022). The e-CNY's programmability contributes to China's goals of building domestic economic resilience and expanding digital financial systems (Li and Huang, 2021). Jiang and Karman (2023) suggest that programmable features might have an impact on regulatory oversight. On the other hand, Saliya (2025) informs that the e-CNY programmability may support monetary

policy innovation. The e-CNY's programmability may reflect China's preference for compliance over monetary policy, arguing that programmability contributes to economic security and can act as an effective deterrent against financial crime.

Programmability can guide the economic and political trajectory of the issuing countries. The Sand Dollar's light approach aligns with the Bahamas' priorities of financial inclusion and economic stability, although it excludes opportunities for conditional policy adjustments (CBOB, 2019). It has the merits of simplicity but might not be suited as precise instrument for interventions. The eNaira's moderate level of programmability is indicative of Nigeria's cautious innovation and provides a medium instrument, without over-regulation's risks. The eNaira can enable greater transparency in the economy of Nigeria, with the potential to scale up to wider programmability, as public confidence and infrastructure capacity may expand. The e-CNY's potential for programmability may be a powerful tool for China's regulatory goals, but it may pose questions on privacy and oversight. The Sand Dollar, eNaira and e-CNY demonstrate how CBDC programmability is not only used to pursue financial targets, but also to interact with other layers of governance and policy.

Regarding the Design and Technology Requirements Dimension, the Sand Dollar prioritises inclusion and simplicity, with robust but lightweight security and technology. Scalability and programmability are limited by design, making it ideal for small economies and less suited for complex policy interventions or high transaction volumes. The eNaira introduces innovation among infrastructural constraints. The security and interoperability aspects are important component of the solution. Adoption rates might be limited by digital literacy of specific groups of the population and potential connectivity issues. Programmability is developing, with potential for broader policy use. The e-CNY may be considered as the most sophisticated and scalable platform, with advanced security, programmability, and integration. In the table below, there is a summary of the key differences across the three CBDCs, for this dimension.

TABLE 7: COMPARATIVE ANALYSIS OF THE DESIGN AND TECHNOLOGY REQUIREMENTS DIMENSION

Dimension	Sand Dollar	eNaira	e-CNY
Modernisation of Payment Systems	- Integrates with existing payment networks and mobile technology. - Enables faster, cheaper domestic payments. - Pioneering role in fintech for small economies. - Focuses on reducing reliance on physical cash, especially in disaster scenarios.	- Aims to digitise payments, reduce the informal economy, and modernise the economy. - Integrated in mobile money and banking apps. - Enables direct peer-to-peer payments. - Allows delivery of government subsidies.	- Enhance payment efficiency. - Integrates with private payment platforms. - Scalable infrastructure to support nation-wide implementation. - Supports cross-border and tourism payments. - Empowers programmable payments. - Supports conditional payments.
Security	- Based on DLT, with transaction immutability, and fraud prevention. - Supports multi-factor authentication (PIN, biometrics). - Encrypts data. - Its simplified architecture may face scalability and cyber challenges. - The two-tier model through AFI for KYC might become a vulnerability.	- Permissioned DLT managed by CBN. - Advanced security features (biometric authentication, PIN, two-factor, USSD). - Sound cybersecurity protections with intrusion detection.	- Multi-layered security reflecting digital sovereignty. - Dual offline wallet system for secure device-to-device payments. - Advanced cryptography, biometric authentication, hardware tokens. - Offline transactions may require dedicated standards to avoid reconciliation and fraud issues.
Scalability	- Designed for domestic transaction volumes, suitable for small population. - Decentralised, modular infrastructure allows upgrades. - Potential for regional growth (CARICOM), but technical limitations exist. - Cost and infrastructure may constrain scalability.	- Scalability might be limited by infrastructural issues, device penetration, and budget. - Modular upgrades possible, but rural connectivity and digital literacy of the population might become concerns.	- Hybrid platform optimised for high transaction volumes. - Centralised engine ensures speed and control. - Processing capabilities of millions of transactions tested in pilot projects. - Urban scalability proven, rural areas might need further infrastructure.

Dimension	Sand Dollar	eNaira	e-CNY
User Experience	• Simple, minimal UI for all age groups and digital literacy levels. • Multilingual support, offline payments. • Easy onboarding, adjustable accessibility features. • Designed for inclusion, especially in rural areas. • Offers incentives (discounts).	• Minimalistic mobile app with large icons, tutorials, and help desk. • Integrates with bank accounts and mobile wallets. • Usability improved over time. • Offers incentives (discounts, reduced fees).	• Advanced UI with voice and facial recognition. • Simplified functions and educational resources for inclusivity. • Compatibility with public services. • Offers incentives (discounts, reduced fees).
Technology Requirements	• Hybrid system, designed with end-to-end encryption and two layers of secure data storage • Permissioned DLT, specifically the NZIA Cortex DLT, provided by NZIA Limited (later rebranded as Movmint). • Offline operation for low-bandwidth environments. • Accessible via smartphones, SMS. • Potential power and internet issues in remote islands.	• Developed upon Hyperledger Fabric platform, a permissioned DLT, ensuring security. • Mobile app and USSD codes for accessibility through feature phones. • Infrastructure constraints were detected (power, internet, availability of devices).	• Custom platform, with multi-layer security, which runs on a multi-site, high availability infrastructure capable of guaranteeing business continuity and 24/7 services • Secure hardware, encryption, biometrics. • Dual offline payments. • Presence of a digital ecosystem that increased the adoption rates.
Interoperability with Payment Systems	• Interfaces with bank wallets, POS systems. • Performs QR code payments and peer-to-peer transactions. • Does not support NFC technology. • Complaint with privacy laws.	• Interfaces mobile wallets and bank accounts. • Enables payment through QR and NFC technology. • Merchant payments via existing POS apps. • Compatible with mobile money providers. • International remittances supported.	• Integrates with banks and payment providers (Alipay, WeChat). • Enables payment through QR and NFC technology. • Offline payments for limited connectivity zones. • Part of m-CBDC Bridge for cross-border interoperability, with a pilot ongoing in Hong Kong.

Dimension	Sand Dollar	eNaira	e-CNY
			• Compatibility with IoT for machine-to-machine payments.
Programmability	• Programmability is limited, focused on simple transfers and disaster relief. • Programmability may be limited to programmable transfers to areas involved in potential natural disasters. • Simplicity aids adoption but limits policy interventions.	• Early-stage programmability for welfare funds, subsidies, and tax automation. • The platform enables conditional transfers. • Potential for expanded features as infrastructure and confidence grow.	• Programmability for conditional payments. • Enables multiple policy tools (incentives, subsidies, discounts). • Programmable features can offer sophisticated policy tools. • Powerful tool for economic objectives.

Source: Author's elaboration.

C. SOCIO-ECONOMIC AND FINANCIAL INTEGRATION

3.1.13. DISTRIBUTION MODEL

The distribution model is the mechanism by which the CBDC becomes accessible to users. In one-tier retail distribution models, CBDCs are issued to consumers directly by central banks, reducing the need for financial intermediaries. Two-tier retail models use intermediaries for the distribution of CBDCs and foresee the possibility for central banks to issue CBDCs to the public, leveraging existing financial institutions for the distribution, and allowing banks to serve as CBDC authorised financial intermediaries, with the oversight of national monetary authorities. Through wholesale models, CBDCs can be issued to financial institutions for interbank transactions and settlement.

The Sand Dollar uses a two-tier distribution mechanism associated with traditional banks and Approved Financial Institutions (AFIs) for the circulation of the digital currency. Users are scrutinised through KYC processes. The digital wallets issued have different transaction and balance thresholds, depending on the level of identification provided (CBOB, 2019). Lower end wallets need little personal information, allowing greater accessibility, while keeping anonymity for small transactions. By utilising Sand Dollar-enabled digital wallets, available on mobile phones, the Sand Dollar may reduce costs of entry for financial services (CBOB, 2023h). From an economic point of view, two-tier models draw on existing institutions to access marginalised groups, proving effective in geographically difficult countries such as the Bahamas (Wright et al., 2022). Through the two-tier model, the Sand Dollar offers centralised control and decentralised distribution across regulated financial institutions, it is strategically positioned to improve access in geographic isolated regions of the Bahamas, to tackle logistical issues and to increase digital financial services access. Wenker (2022) suggest that models of distribution that leverage local financial intermediaries, such as the Sand Dollar, could be beneficial for unbanked people with low digital literacy levels, as they could rely on professional institutions with local expertise. With the circulation of the Sand Dollar through authorised banks, the CBOB can control currency flows without depriving consumers of privacy (Sisodia, 2024). The intermediated approach has been valuable in combating financial exclusion through the existing institutions' networks to reach remote communities, and it also allows non-bank organisations to play a crucial role, providing access to unbanked communities on remote islands.

The eNaira adopts a two-tier intermediated model, where the CBN manages directly the eNaira through the Digital Currency Management System (DCMS), to streamline transactions,

and then, financial institutions, and agents distribute the eNaira to individuals and businesses (Alberola and Mattei, 2022). The eNaira is perceived to be Nigeria's attempt to stabilise the economy, by enhancing the Nigerian Naira's status and increasing financial transparency. The issuance of eNaira would be conducive to improving financial inclusion, by offering an open access digital currency to unbanked masses, especially in rural communities (Abdullahi and Nasuha, 2025). The eNaira is a legal tender and has parity with the physical Naira. The eNaira's intermediated model offers sovereign control over issuance and distribution by the CBN, delegating the KYC and onboarding procedures to the authorised financial intermediaries (CBN, 2021a). Nigeria has a high mobile penetration, but the digital divide is still present, limiting the potential of the eNaira in rural and subserved regions (World Bank, 2025b). This raises concerns on whether the intermediated distribution mechanism can be considered as economically effective in rural areas, where the banking infrastructure is limited. Some researchers argue that individuals may lack the mobile technology required to use the digital wallets (Sadat and Shaba, 2025). The eNaira provides an inclusive platform but efforts should be made by the CBN, to bridge both infrastructural and literacy divides.

The e-CNY program in China implemented a two-tier distribution system that combined bank partnerships with central oversight by the PBoC. With this operation model, the PBoC issues the digital money to licensed operators (traditional banks and payment institutions), who release the e-CNY to the public and offer exchange services between the digital and physical currency (PBoC, 2021). This two-tier architecture facilitates adoption, improves financial stability, and allows the PBoC to retain supervision over e-CNY's issuance and supply, while leveraging the network and customer interface of the commercial sector, capitalising on banks' branches to ease user engagement and to boost economic adoption, in line with China's strategic goals of economic self-sufficiency and domestic control (Huang and Li, 2023). The rationale for the e-CNY's distribution mechanism coincides with China's intention to promote digital payments as part of its economic modernisation plan. Fullerton and Morgan (2022) mentioned that this model enables the Chinese government's larger economic agenda to reduce dependence from the private sector for digital payments, while offering scalability and sustainability. The e-CNY also offers dual offline technology, meaning transactions can be executed without an internet connection, thus supporting rural areas, without the need for intermediaries. The e-CNY's two-tier model is an integrated strategy combining central supervision and market engagement. The e-CNY's distribution structure achieves the economic and political goals, since it enables the PBoC to provide financial oversight and to reduce the reliance of the public on private payment channels. Furthermore, researchers have also pointed out that the e-CNY strengthens national currency sovereignty, and it offers an

alternative option to foreign-led payment systems, in line with China's larger geopolitical interests (Saliya, 2025).

Researchers reveal that no single model of distribution can be considered as optimal, as models depend on how each country evaluates accessibility, control, and scalability. The Sand Dollar's intermediated model has been able to achieve moderate adoption in rural Bahamian areas. The eNaira's attempt to drive better governance has led to the adoption of the same two-tier distribution model (CBN, 2021a). The e-CNY two-tier model offers regulatory compliance and control mechanisms that suit its internal governance mechanisms. As the literature suggests, the distribution models cannot be considered as a simple technical decision but a rather complex choice, influenced by economic, political and technological circumstances. Further research should evaluate how users' trust influences CBDCs' adoption and the correlation between distribution models and CBDCs' trust levels. The combined insights from future research evaluations of CBDCs' success rates may guide central banks in the selection of the most appropriate implementation model.

3.1.14. ADOPTION AND USAGE

The adoption rate is a key measure for the success of CBDCs. Adoption metrics for each CBDC may differ, showing public acceptance within varying degrees, depending on the distribution model, on the associated infrastructure and on demographic factors. The adoption of CBDCs may differ in relation to the diverse population groups and may be low for residents in remote areas, with partial exposure to digital technologies (World Bank, 2018). Governmental support and public trust from citizens are important elements to foster CBDCs' adoption rates (Prasad, 2021).

The Sand Dollar recorded a phased adoption during the past years, with initiatives ongoing to promote among the public its use for everyday transactions. In December 2023, approximately 119,000 digital consumer wallets of the Sand Dollar were open, with approx. 1,800 active merchant wallets, being supported by a network of partnerships with banks to ensure interoperability (Anthony, 2025). The Sand Dollar has real-world effects in terms of financial inclusion, across local communities (Wright et al., 2022). The popularity of the Sand Dollar in the Bahamas is due to its ease of use and backing by the government, with limited concerns to data privacy (Wenker, 2022). This CBDC was also challenged over its limited application, suggesting that limited adoption rates may prevent the Sand Dollar to fully realise its potential (Sisodia, 2024). Another concern raised is related to the impact of the digital literacy of the Bahamian population on the adoption rate (Haans, 2024). The Sand Dollar has made

reasonable economic contribution by improving transaction and cash processing efficiency (CBOB, 2023e). The Sand Dollar transactions helped to infuse local economies with trade from remote communities. Depending on its adoption rate, researchers may ascertain how well it can affect macroeconomic stability indicators, like GDP growth or inflation rate (Wright and Todd, 2024). The Central Bank has established commercial agreements with Authorised Financial Institutions to integrate the Sand Dollar into point-of-sale solutions. The Bahamas has expanded the Sand Dollar's footprint through digital infrastructure improvements, implementation across merchants and integration with foreign payment networks. The CBOB has worked to improve the Sand Dollar and to assess its potential for the expansion in the Caribbean region (CBOB, 2019).

The eNaira is expected to make long term positive impact in Nigeria, incentivising economic growth and easing inflationary pressures over time through lower transaction costs (CBN, 2021a). Statistics indicate that adoption rates of eNaira may be limited, and this might impact the financial inclusion initiative (Akpan et al., 2024). Low adoption rates might be attributed to due to economic and societal factors (Abdullahi and Nasuha, 2025). According to the IMF (2024a), in 2024 there were 13 million wallets of eNaira, with 854,512 transactions equivalent to a value of N29.3 billion, mainly due consumers to merchants' dealings. The eNaira's adoption may be related to cash-driven habits, digital divide, and lack of incentives for users to shift to CBDCs (Ozili, 2023c). The eNaira's adoption rates may be influenced by infrastructural constraints and may require support policies to build trust and usability. Ozili. (2023a) enumerates the potentials of the eNaira, but also the challenges of its adoption. He points to technical constraints and lack of public knowledge as the major obstacles. A significant percentage of the population are uneducated when it comes to digital financial services (World Bank, 2025b). Cultural habits and consumer behaviour regarding cash payments might be hard to change and require trust and widespread knowledge (Idisi et al., 2024). Nigeria's internet penetration (individuals using the internet as % of the population) stood at 39% during 2023, with good progress year over year (World Bank, 2024). Low adoption rates might have also been due to cybersecurity, fraud and privacy concerns (Ogunrinde, 2023). According to CBN (2021a), effective user experience along with institutional trust play critical roles in achieving adoption. The CBN has issued measures to promote adoption, offering merchants and users incentives such as transaction fees reduction and promotional schemes (CBN, 2023f). The eNaira has been utilised for government disbursement schemes to enable social welfare payments (Obiora, 2023a; CBN, 2023c). Efforts were made to link the eNaira with diaspora-based remittance services (Idisi et al., 2024). The CBN have started educational campaigns about eNaira to encourage its usage,

providing incentives to merchants and developing partnerships with fintech firms to improve accessibility.

The e-CNY is fuelled by China's innovative technological infrastructure, strong government support and common digital payments culture (Bansal et al., 2021). The e-CNY, still in pilot project, was launched in 2020, it is available to 29 cities (at the time of writing), and it integrates with public services and with payment platforms such as WeChat Pay and Alipay (Lyu et al., 2023). The e-CNY has seen an expansion with transaction numbers soaring and a rising public adoption. In July 2024, 180 million personal wallets were created on the e-CNY App, with a total amount of 7.3 trillion-yuan transaction (Mu, 2024). China, through the mBridge project has explored the usage of CBDC across jurisdictions, achieving the minimum viable product (MVP) level (BIS, 2024). Furthermore, cross-border transactions in Hong Kong were enabled by the Monetary Authority of Hong Kong (HKMA and PBoC, 2024). However, there are considerable differences among large cities and rural areas regarding the technological infrastructure and user awareness (Xu and Jin, 2025). This disparity could limit the access to the e-CNY to the marginalised areas. Alipay and WeChat Pay have a long history as established payment systems, to convince businesses to switch to the e-CNY, it would be important to promote awareness of the expected benefits (Wang, 2021). The e-CNY's rapid rollout shows that harnessing existing digital ecosystems may be a successful strategy.

The adoption rate is an essential component of CBDCs' success. The Sand Dollar, e-CNY and eNaira are examples of different strategies, subject to their specific national circumstances, political goals, and technological capabilities. To fully benefit from CBDCs, coordination among central banks, traditional financial institutions and technology companies will be vital to enable successful implementations.

3.1.15. ACCESSIBILITY

Accessibility refers to the ease with which CBDCs are obtained and exchanged by users. It has dependencies upon the technological infrastructure, the user interface, the regulations enacted, and it is meant to include marginalised communities. The adaptability of a CBDC helps to ensure interoperability and to improve user experience. The Sand Dollar, the eNaira and the e-CNY all seek to promote accessibility, but in different ways. The Sand Dollar satisfies the geographic constraints of the Bahamas through its offline capability but necessitates ongoing user education and infrastructure improvements. The eNaira's architecture makes it relevant for Nigeria's diverse groups, but it needs to overcome

challenges of digital literacy, to become a payment tool of choice. The e-CNY's advanced platform set it at the forefront of CBDC development, covering a variety of use cases.

The Sand Dollar brings inclusive access to financial services across the archipelago's islands, simply by using smartphones (CBOB, 2023b). As the Bahamian population spread over several islands, banking services are often unavailable or not easily accessible. For this reason, the Sand Dollar is run through mobile technology. Taking into consideration the technological constraints, the CBOB has developed mobile wallets for smartphones (CBOB, 2020c). With the SMS mechanism, anyone with a simple mobile phone can send and receive Sand Dollars. The Sand Dollar makes mobile payments easier, thus lowering transaction fees and fostering local economic growth (Branch et al., 2025). Moreover, the Sand Dollar wallets work with low bandwidth to help reduce mobile data usage fees. Transactions can be made by using the mobile application for smartphones, providing with technological accessibility different age groups of the population (CBOB, 2020e). This mobile-first strategy is in line with the Bahamian government's emphasis of extending financial services to rural communities, making banking services available to those who would otherwise be unable to obtain them (Wright et al., 2022). The CBOB identified investments in digital infrastructure to improve accessibility further (CBOB, 2023b). The central bank has also collaborated with local banks and mobile phone providers to promote the use of the Sand Dollar, particularly in remote islands, where the access to banks is restricted.

The eNaira was tailored by the CBN, as Nigeria's response to a large unbanked population, suffering from a lack of access to traditional banking services. Nigeria's financial system is characterised by regional gaps in banking infrastructure, and a digital currency like the eNaira may play an important role in financial inclusion (Esoimeme, 2021). In fact, the eNaira serves as a financial inclusion instrument for increasing access to digital financial services among Nigeria's unbanked population, especially in rural areas (Sadat and Shaba, 2025). The CBN has placed mobile access at the centre of the eNaira's architecture, and it seeks to integrate it with Nigeria's existing mobile money services, which are widely used in Nigeria's rural communities. The CBN provides Android and iOS mobile wallet applications, with multiple access points. As smartphones' penetration in Nigeria is still lower than in other developed countries, the eNaira also allows USSD codes for transactions with feature phones (CBN, 2023b). By providing an electronic currency that can be used through mobile apps and USSD codes, the eNaira tries to reduce the informal economy, lower transaction fees and enable foreign remittances (Ogunrinde, 2023). Recent analysis indicates that the limited internet connectivity and the low digital literacy might represent entry barriers, especially in rural areas (Ozili, 2023b). The CBN has initiated awareness campaigns and educational programmes to

improve knowledge, with adoption rate influenced by this factor (Akindipe, Akhimie and Olonade, 2023).

The e-CNY can benefit from a technologically advanced infrastructure. The PBoC have launched the e-CNY pilot programme in 29 cities (at the time of writing) and has targeted also communities, who are usually not customers of traditional banking services but possess mobile phones. The PBoC addressed accessibility by creating a simple mobile application that can integrate with the nation's existing digital payment infrastructure (Xia, Gao and Zhang, 2025). The e-CNY's smartphone app is compatible with leading digital wallets, such as Alipay and WeChat Pay, already widely used in China (Fullerton and Morgan, 2022). Adoption rates are supported by a simple interface, able to provide consumers with an intuitive user experience. The e-CNY supports hardware wallets (e.g. physical cards and wearable devices), which allow users without smartphones to adopt the e-CNY (Branch et al., 2025). Moreover, the dual offline payment option also supports inter-device payments without internet, enabling the e-CNY to work even in places where network coverage isn't available (Mu, 2023). For the e-CNY, the oversight aspects are compelling, as they could have an impact on user confidence and on the overall acceptance of the currency, especially in rural areas, where people may be more sensitive of regulatory compliance (Cheng P., 2022). The government stepped up efforts to promote digital literacy campaigns to encourage the usage and to turn the e-CNY into a cornerstone of China's digital economy (Branch et al., 2025).

The design of a CBDCs can influence its accessibility, and low digital literacy rates may remain an important barrier. The Sand Dollar has focused on accessibility, prioritising its financial inclusion objectives, however intermittent internet connectivity and low user awareness may slow down the adoption rates. The CBOB has started educational campaigns and dedicated infrastructural investments to address these problems. In Nigeria, the eNaira aspires to formalise the large informal economy, but issues in the provision of electricity and the availability of internet networks may require dedicated initiatives at national level. The technologically advanced e-CNY represent a powerful tool for residents, however there is a concern that it may deepen the digital divide across different groups of the population. The digitally educated people with availability of smartphones might benefit from the e-CNY more than the low-income groups or residents in remote areas. The PBoC has explored alternatives like physical cards, IoT and wearable devices to increase the accessibility of the e-CNY. Future research may investigate the long-term effects of CBDC adoption, through comparative studies with a wider spectrum of nations, and an objective to formulate global standards for CBDCs. Further coordination between national monetary authorities, financial institutions, fintech, and international organisations may be needed to identify new accessibility standards.

3.1.16. INTERNATIONAL USE FOR CROSS-BORDER TRANSACTIONS

The reliance on multiple correspondent banking relations, together with the use of outdated technology may be considered the rationale for current time-consuming and expensive cross-border payments. The implementation of CBDCs may enable better cross-border payments, by allowing central banks to connect directly with commercial banks and payment service providers, thereby enhancing liquidity and lowering counterparty risks (Boar et al., 2022). CBDCs hold the potential to decrease both transaction costs and settlement times, while reducing present inefficiencies within the international payment systems (World Bank, 2021). CBDCs can encourage trades and simplify remittance processes for countries such as the Bahamas, Nigeria e China, positively impacting their economies. In the Bahamas, the Sand Dollar focuses primarily on domestic market, with a potential utilisation across the CARICOM region. Although the eNaira is more advanced at enabling cross-border remittances and has a dedicated operational framework and payment option for recipients of diaspora remittances (CBN, 2023g), it may remain limited to the Nigerian market. China has piloted its CBDC internationally, in a bid to reduce its dependence on foreign currencies (BIS, 2023f).

The Bahamian dollar is pegged on a 1:1 relationship with the US dollar, and its GDP was in the region of US\$14.3 billion in 2023 (World Bank, 2025a). The small economy of the Bahamas and the currency peg may reduce the potential number of transactions that could be executed using the Sand Dollar (CBOB, 2019). The Sand Dollar's innovative platform may be able to serve well the transactions in the domestic market, and to perform payments for tourists, in consideration of the possibility for non-residents and visitors to fund Sand Dollar wallets with foreign currency, with a wallet holding limit of 500 Bahamian Dollars. However, it presents limited potential to address cross-border payments. Without pilots planned for international interoperability, the Sand Dollar may be limited to domestic users. Despite a good level of security and usability, the Sand Dollar's technology may be more suitable for domestic payments (Branch et al., 2025). The Sand Dollar's limited interoperability with international payment networks may prevent its use beyond national borders. However, Authorised Financial Intermediaries that offer Sand Dollar wallets may enable users to procure FX in exchange of Sand Dollars to complete transactions in foreign currency (CBOB, 2025). The Sand Dollar confirms its appropriateness for low volume, regulated environments, although the Bahamas small open economy may limit its potential for international expansion (Wright and Todd, 2024).

The eNaira is available only in Nigeria (CBN, 2021a); however, through interoperable payment services, it may the potential to perform transactions across the African Continental Free Trade

Area, simplifying payments across borders. From an economic perspective, the eNaira seeks to reduce transaction costs, to streamline cross-border commerce, and to bring transparency into the activities of the informal economy. With its dedicated operational framework and payment option for the recipients of diaspora remittances, the eNaira may help Nigeria's population living abroad and in-country, by lowering the fees related to international remittances (CBN, 2023g). Moreover, the eNaira is expected to improve the revenue collection and to curb financial crime (Idisi et al., 2024). By decreasing the reliance upon foreign payment systems, the eNaira fosters Nigeria's sovereignty on payment systems, allowing the CBN to exercise more control on the remittance flows.

The e-CNY may represent an instrument for China to further increase the internationalisation of the Renminbi (RMB) (Bencivelli and Savini Zangrandi, 2023). The e-CNY may transform China's payment methods, further reducing dependence from cash (Zheng, 2023). Additionally, the e-CNY could reduce transaction fees and increase the speed of cross-border payments, a promising prospect for international enterprises (Yang and Zhou, 2022). Regarding cross-borders payments, the e-CNY can facilitate global trade by supplying a viable alternative to the current payment mechanisms (Wang, 2021). By providing an alternative to the US dollar in the global commerce, China could increase its geopolitical reach (Chen, Alonso-Trabanco and Zhang, 2021). In internationalising the Renminbi, China may wish to lessen its reliance on the international status quo (Chorzempa and Spielberger, 2025). In consideration of the China's Belt and Road Initiative (BRI), the e-CNY may ease trade settlement and lessen foreign exchange exposure for involved countries (Caudevilla, 2022). Pilot projects for international transactions were initiated with Hong Kong (HKMA and PBoC, 2024). The PBoC participated actively in the mBridge project, developed by the BIS to explore the settlement and operations of multiple CBDCs with other international partner central banks (BIS, 2024). With a strong infrastructure and pilot initiatives, the e-CNY demonstrates China's ability to position its CBDC as an alternative standard (Peters, Green and Yang, 2020). The e-CNY has drawn geopolitical attention, because its international use might have implications for the existing financial equilibrium and weaken the traditional operating frameworks (Caudevilla, 2022). The e-CNY may allow China to continue to maintain control on capital flows, supervising its financial system (Cheng G., 2022). The e-CNY has potential to revolutionise cross-border payments; however, challenges remain, as its adoption may rely on the ability of foreign institutions to endorse the CDBC.

The execution of cross-border transactions through CBDCs can be technically challenging but rewarding. The Sand Dollar has a more domestic approach and allows tourist payments, the eNaira strives to attract international remittances from the Nigerian expats. Thanks to its

advanced software, and technological infrastructure, the e-CNY represents a potential solution able to support international trade. Future growth may depend by how these countries may achieve technical interoperability, foster global cooperation, and steer geopolitical issues.

Regarding the Socio-Economic and Financial Integration Dimension, the Sand Dollar's two-tier distribution model is effective for inclusion and privacy, leveraging intermediaries to maximise reach. The eNaira's two-tier model offers dedicated support to encourage adoption, while the e-CNY's two-tier model combines central oversight with market engagement, supporting scalability and rural access. The Sand Dollar demonstrated progress in the adoption and usage rates, driven by the governmental support and private sector partnerships, but may face technological and literacy concerns. The eNaira's adoption might be impacted by cultural resistance and infrastructure constraints, notwithstanding incentives and campaigns. The e-CNY leads in adoption due to integration with existing platforms and strong government backing. All three CBDCs prioritise mobile access and inclusion, but face challenges from digital literacy and divide across the countries. The Sand Dollar and eNaira offer wallet solutions through SMS, low-bandwidth applications and feature phones, while the e-CNY benefits from China's advanced infrastructure, but might need to promote awareness for low-income groups or residents in remote areas. On the international use, the Sand Dollar has mainly domestic aspirations, including the touristic payment flows, with no cross-border capability. The eNaira supports cross-borders remittances and potentially international trade, aiming for future regional impact. The e-CNY is positioned for international use, with pilot projects with Hong Kong and strategic integration with other partner central banks through the mBridge project. An outline of main features of the three CBDCs for this dimension is detailed in the table below.

TABLE 8: COMPARATIVE ANALYSIS OF THE SOCIO-ECONOMIC AND FINANCIAL INTEGRATION DIMENSION

Dimension	Sand Dollar	eNaira	e-CNY
Distribution Model	- Two-tier system. The CBOB issues CBDCs to Approved Financial Institutions (AFIs), who then distribute to users. - The model leverages local intermediaries, combining centralised control with decentralised distribution. - Non-bank organisations also play a role in reaching unbanked communities.	- Two-tier system. The CBN manages issuance via the Digital Currency Management System (DCMS). Agents distribute the eNaira to individuals and businesses. - The model aims for sovereign control and streamlines transactions. - High mobile penetration is limited by a persistent digital divide, especially in rural areas.	- Two-tier system, where the PBoC issues e-CNY to licensed banks and payment institutions, who then distribute to the public and provide exchange services. - This model combines central oversight with market engagement, leveraging commercial banks' networks for user adoption. - Its dual-layer architecture enables online and offline transactions.
Adoption and Usage	- Gradual adoption model. - In December 2023, there were approx. 119,000 digital consumer wallets of the Sand Dollar were open, with approx. 1,800 active merchant wallets, supported by the intermediation of the Authorised Financial Institutions. - The CBDC has contributed to transaction efficiency and local economic growth, but adoption is influenced by user awareness and infrastructure.	- Incremental adoption model. - In 2024, approx. 13 million wallets and 29.3 billion transactions. - Actual usage might be constrained by cash-driven habits, and digital divide. - Incentives for adoption and integration with remittance services. - Supports government and social welfare payments. - Supported by informational campaigns.	- Rapid expansion through pilot projects across 29 cities, with 180 million personal wallets created by July 2024, and 7.3 trillion yuan transacted. - Adoption rates high in urban areas, thanks to the advanced infrastructure. Rural uptake may be decisive. - Pilot projects and government campaigns support ongoing expansion. - Important to facilitate access in rural areas, aligning with country's goals of economic self-sufficiency and currency sovereignty.

Dimension	Sand Dollar	eNaira	e-CNY
Accessibility	• It has a mobile-first approach. It supports smartphones with low bandwidth application and SMS payment options. • Offline capabilities are available. • Collaboration with banks and mobile providers to promote use in areas with limited bank access. • Designed to reach remote islands and marginalised groups, lowering transaction fees and fostering local growth. • Educational campaigns to improve digital literacy level of the population.	• Multi-channel access. Mobile apps for smartphones. USSD codes for feature phones, targeting unbanked and rural areas. • Offline capabilities. • Aims to reduce the informal economy. • Enable remittances with dedicated payment option and operational framework. • Faces barriers from intermittent electricity, and low levels of digital literacy. • Awareness campaigns and educational programmes ongoing to improve adoption.	• The e-CNY has advanced integration, its app works with existing digital wallets (Alipay, WeChat Pay), soft and hard wallets (IoT, wearables), and supports advanced offline payment and public services. • High accessibility in urban areas, but rural and low-income populations might face challenges, due to digital divide. • The authorities promote digital literacy and alternative access methods to increase inclusion.
International Use	• The Sand Dollar has mainly a domestic focus, including payment flows from visitors and non-residents. It is primarily designed for local transactions, with no cross-border potential at this stage. • The Sand Dollar's technology is best suited for regulated, low-volume domestic payments. • Its small scale restricts international expansion.	• The focus of the eNaira is domestic with support for cross-border remittances, to reduce reliance on foreign payment systems. • It enhances revenue collection and payment sovereignty but remains dependent on Nigeria's local market and infrastructure.	• Cross-border pilots ongoing with Hong Kong Monetary Authority and through the mBridge project. • The e-CNY supports China's ambitions for currency leadership, and it is a strategic tool for RMB internationalisation in line with the Belt and Road Initiative. • It has the potential to innovate payments and to reduce dependence on foreign currencies and payment systems.

Source: Author's elaboration.

D. SUSTAINABILITY AND INCLUSIVITY

3.1.17. *PRIVACY*

As a key component of a CBDC's design and implementation, privacy requires ongoing cross-sector research to identify the optimal degree of protection, within appropriate regulatory purposes. Privacy represents a fine balance between the rights of the individuals and the authorities' interest in persecuting crime (Ballaschk and Paulick, 2021). The safeguard of privacy entails protecting users' transactional data against intrusion and tampering, implementing adequate controls. Data confidentiality may impact the public's trust and the success of CBDCs' initiatives. CBDC's privacy features may have a direct effect on financial inclusion and consumer trust. Tiered KYC models are employed by the three CBDCs analysed, to reach a compromise between privacy and regulation, whereby CDBC's wallets may be opened according to specific levels of KYC identification and documentation provided, allowing higher transactional and holding limits to users who complete higher level of KYC identification. In allowing easy access for basic wallets, with no identification required, the Sand Dollar, the eNaira and the e-CNY place emphasis on financial inclusion.

The Sand Dollar design embeds privacy protections to satisfy international regulations (CBOB, 2019). Payment information is encrypted in each touchpoint of the Sand Dollar, with protections designed for personal data (Branch, Ward and Wright, 2023). The CBOB keeps minimal information to execute the required monitoring, with security measures in place to prevent abuse (Wenker, 2022). As presented in table 9, the Sand Dollar allows for a tiered mechanism of KYC, in which the wallet holding and transactional limits are set by the level of user identification and regulatory disclosure (CBOB, 2024). The tiered KYC mechanism separates the users into limited, anonymous users who can perform low-value transactions and fully identified users who are entitled to operate higher-value transactions. Anonymity is guaranteed for low value transactions, while high value transactions require a deeper identification of users (CBOB, 2024). The basic wallet has fewer information requirements, and enables users to transact with smaller amounts, making them more accessible to a wider audience, but still compliant. The Sand Dollar's privacy framework highlights that accessibility can coexist with regulatory oversight, enabling an alignment between privacy, AML principles and CFT rules (CBOB, 2021d). The privacy architecture of the Sand Dollar could potentially serve as a model to encourage digital inclusion at a low privacy cost for small economies (Wenker, 2022).

As presented in table 9, The eNaira has a similar multi-tiered KYC approach, with different identification thresholds, associated with varying transactional limits (CBN, 2021a). According to Ree (2023), there are several types of digital wallets available to the public, which can be obtained through different levels of authentication and KYC. Entry-level wallets require minimal identification, such as a phone number and National Identification Number (NIN), with more comprehensive identification required for higher level wallets. When compared to the other two CDBC's, the limits imposed to the tiered wallet of the eNaira seem to be quite low. The eNaira's acceptance of NIN system reveals the convergence between national ID and CBDC privacy. Though this approach is suitable to balance accessibility and regulatory oversight, researchers warn that it might impact privacy, since from Tier-1 wallet, regulators may have access to user data for monitoring purposes, compromising public trust in privacy features (Omotubora, 2024). In the past, privacy concerns for the eNaira were related to data security and handling of personal information (Abdullahi et al., 2024). The achievement of public trust necessitates consistency and transparency and should be supported by institutional awareness campaigns. The eNaira has complied with the data protection legislation (CBN, 2021b). It implemented data privacy principles to protect users and to respect the privacy framework (CBN, 2021a).

According to Mu (2022), the e-CNY transact through a controllable anonymity principle with transaction information being anonymised up to a certain threshold amount, and user data shared with the authorities for transactions with larger amounts, as detailed in Table 9. The e-CNY have specific features, in line with the regulatory framework adopted in China, that allows for oversight of transactional data. In fact, higher value transactions can be monitored and accessed by the PBoC to prevent money laundering and to combat financial crime (Mu, 2023). This approach reflects China's consideration of regulatory compliance over privacy, and it is common across the three CBDCs analysed in this research. Some authors argue that there may be a risk related to the supervision (Fanusie and Jin, 2021). The controlled anonymity of the e-CNY might be exposed to compliance monitoring and to over-disclosure of transaction data (Tronnier and Qiu, 2024). Mu (2023) ensures that the design of its CBDC cater for national security and economic stability requirement.

In the following table, it is possible to find a recap of the tiered privacy levels for each wallet of the three CDBC's.

TABLE 9: TIERED PRIVACY LEVELS, DOCUMENTATION REQUIRED AND LIMITS FOR EACH CDBC'S WALLET TYPE (FX RATES AS OF 26 NOV 2025)

Type of Wallet	Sand Dollar	eNaira	e-CNY
Personal I	Tier-1 - No identification document is required. - Wallets top up can be made through FX. - Monthly transaction up to BSD1,500. - Wallet holding limit up to BSD500 - Peg = BSD 1:1 USD. - Specific transactions (e.g. utilities) are excluded from the limit.	Tier-0 - Phone number. - No identify information required. - No need for bank account. - Daily transaction limit of NGN20,000 (USD14). - Balance/ Speed Wallet up to NGN120,000 (USD83).	Tier-4 - Required cell phone number without valid ID (telecom operator cannot disclose the identity of the phone number holder to third parties, including the PBoC). - Single transaction up to CNY2,000 (USD283). - Daily cumulative up to CNY5,000 (USD707). - Balance/ Wallet up to CNY10,000 (USD1,414). - Annual spending up to CNY50,000 (USD7,070).
Personal II	Tier-2 - Benefits from simplified due diligence, with only a government identification required. - Possible link with a bank account. - Higher wallet amounts - Monthly transaction limit of BSD10,000. - Wallet holding limit up to BSD8,000. - Peg = BSD 1:1 USD.	Tier-1 - Phone number with verified National Identification Number. - Identification data (name, date of birth), without verification. - No need for bank account. - Daily transaction limit of NGN50,000 (USD34.5). - Balance/ Speed Wallet up to NGN300,000 (USD207.3).	Tier-3 - Required cell phone number and valid ID. - Single transaction up to CNY5,000 (USD707). - Balance/ Wallet up to CNY20,000 (USD2,828).

Type of Wallet	Sand Dollar	eNaira	e-CNY
Personal III	Not available	Tier-2 • Phone number with verified NIN. • Basic identity information (e.g., photo, name, date of birth); evidence required for submitted information; customer to be verified through official databases • Bank account required for Bank verification number (BVN). • Daily transaction limit of NGN200,000 (USD138.2). • Balance/ Speed Wallet Limit up to NGN500,000 (USD345.5).	Tier-2 • Required cell phone number, valid ID, personal bank account. • In-app verification process. • Single transaction up to CNY50,000 (USD7,070). • Account up to 500,000 RMB (USD70,700).
Personal IV	Not available	Tier-3 • Full identify information and evidence (including proof of address and physical presence in the address) in pursuant to CBN's AML/CFT Regulation 2009. • Risk-based verification performed. Bank account required for Bank verification number (BVN). • Daily transaction limit of NGN1,000,000 (USD702). • Balance/ Speed Wallet up to NGN5,000,000 (USD3,510).	Tier-1 • Required cell phone, valid ID, personal bank account. • In-person verification and signature with an authorised operating institution. • No limits on account or transaction limit.

Type of Wallet	Sand Dollar	eNaira	e-CNY
Business	Commercial - The proof of regulated status is mandatory. - Self-employed may count as individuals, depending on specific parameters (e.g. activity levels). - Wallet holding limit up to BSD1,000,000. - No transaction limit. - Peg = BSD 1:1 USD.	Merchant - Bank account, Tax Identification Number, business certificate, Bank Verification Number of CEO, email. - KYC in accordance with AML and CFT Regulations. - Wallet without threshold.	Merchant - Identification required. - Full list of documentation required, subject to contracts with intermediaries.
Source	(CBOB, 2019; CBOB 2024)	(Ree, 2023)	(Mu, 2022; HKMA, 2025; Xu K., 2022)

Source: Author's elaboration.

3.1.18. INCLUSIVITY

The concept of financial inclusion represents the provision of equal financial services across diverse population segments, according to World Bank (2018). The unavailability of bank access limits economic growth and it undermines conditions for the alleviation of poverty, fuelling inequality. CBDCs could help to close this gap, using digital technology to offer universal financial services (Auer, Cornelli and Frost, 2020). Minimalism in the user interfaces, and usability on low-end devices encourage the adoption rates, especially in marginalised communities who do not possess digital literacy. The Sand Dollar and the eNaira have a common target to improve financial and digital knowledge to develop domestic financial inclusion.

The geographical spread of the Bahamas made it an ideal test case for digital currencies to support marginalised communities (CBOB, 2020c). By enabling payments in areas without bank facilities, the Sand Dollar is geared toward financial inclusion. In fact, the Sand Dollar's architecture specifically addresses financial inclusion, by offering digital financial services through mobile phones, appealing to unbanked and underbanked populations in remote islands (Wright et al., 2022). Providing an alternative to bank accounts lowers the barriers of entry and transaction fees, making them affordable for the low-income users. The Sand Dollar can be accessed using mobile wallets for smartphones and SMS, making it more accessible to people of all technological backgrounds. Rolle (2019a) notes that these types of services may stimulate economic activity and could facilitate long-term economic growth in the

Bahamas. Through its mobile application and with real-time transfers, the Sand Dollar may enable additional services to users to participate in the economy more effectively (CBOB, 2019). By cutting transaction fees, the Sand Dollar enhances financial participation for everyone, including those in rural areas. The access to affordable services bolsters financial inclusion, by reducing economic barriers (Anthony, 2025). The CBOB has worked in partnership with local businesses and government entities to make the Sand Dollar available for daily expenditure such as for supermarkets and utility bills (CBOB, 2023e). The Sand Dollar uses a safe, DLT-based system that allows offline payments, an important aspect, considering that internet connectivity across the islands is not stable (Sisodia, 2024). Although the Sand Dollar has proven to be effective for financial services, there is still room for improvement. In its design, the Sand Dollar is firmly committed to financial inclusion, it supports offline transactions, a critical feature for the Bahamian islands (CBOB, 2019). Since its launch, the Sand Dollar has made digital finance accessible to people living across the archipelago, making transactions faster and economic participation more inclusive (CBOB, 2023a). Branch et al. (2025) underline this decision as morally significant, because it promotes inclusion for the poor and bridges the disparity between access to financial services.

The eNaira's purpose is to bring Nigeria's large informal economy into the financial system (Ree, 2023). The eNaira targets Nigeria's vast unbanked and underbanked population (CBN, 2022). Barriers to entry are mitigated by eNaira's compatibility with mobile money platforms and its tiered KYC processes (Ree, 2023). Easy to use, the eNaira works with smartphones as well as ordinary feature phones, more common in Nigeria's rural areas, representing the eNaira's effort to make mobile technology more inclusive (CBN, 2023b). In fact, with USSD-based transactions, the eNaira can be used by people without smartphones or internet connection. The CBN has also collaborated with mobile service providers for the delivery of services at low prices (CBN, 2023a). The eNaira reduces transaction costs on small transfers, which helps to facilitate the low-income groups and users in remote areas (CBN, 2022). Ogunrinde (2023) examines the eNaira's use and challenges to reach the poor, especially in Nigeria's rural areas. Unstable mobile network coverage may represent a major barrier to mainstream adoption (Idisi et al., 2024). Ogunrinde et al. (2023) confirms that the eNaira is on a path to facilitate financial inclusion. Digital literacy might remain an obstacle to adoption, particularly in rural regions, where users aren't familiar with digital payments (Sadat and Shaba, 2025). Furthermore, the user base might be affected by low levels of digital financial services and hence, the adoption rate might be impacted (Lee, 2025). Educational and support activities shall continue, requiring considerable efforts in terms of resources and time (Abdullahi and Nasuha, 2025). Cybersecurity and fraud concerns, as well lack of trust in online financial services, may continue to have an impact on the adoption rates (Ozili, 2025). In its

quest for inclusivity, the CBN may prioritise to overcome barriers, through educational campaigns and implementation of reliable technological infrastructure.

The e-CNY is designed to broaden financial inclusion in the rural areas without compromising regulatory oversight (PBoC, 2021). Chin (2025) addresses the e-CNY's advocacy in favour of financial inclusion and its impact on financial services access. The e-CNY's two-tier distribution model may favour inclusion, with existing banks authorised to distribute the digital currency and to support the end users (Li and Huang, 2021). The e-CNY provides incentives and low-cost services in rural areas that attract several groups of the population (Branch et al., 2025). The Chinese authorities have encouraged inclusivity through subsidies in specific areas (Kharpal, 2021). Economic incentives (lotteries and discounts for using the e-CNY) have been introduced to encourage people of all ages to adopt it (Kshetri, 2022). This model has been celebrated as inclusive, but researchers raised questions on its viability over time (Liu et al., 2022). The e-CNY is based on high-tech systems enabling payments in real time (Chin, 2025). The e-CNY works online as well offline and takes advantage of China's vast telecom network to execute payments (Cheng P., 2022). The e-CNY's inclusivity is influenced by the many payment services in place and by the diverse digital expertise of the population (Huang and Li, 2023). The choice of a technologically advanced platform for the e-CNY may have an impact on the country's digital divide. Connected cities are more likely to gain more advantages from the e-CNY's mass adoption, while remote or rural places with low smartphone penetration or intermittent internet access may not gain the full benefits (Prasad, 2022). The e-CNY advantages may remain limited for remote regions with a smaller percentage of the population with digital abilities (Chin, 2025). To mitigate this, the PBoC has introduced hard wallets for wearables and IoT devices, and an inclusive measure to provide services to foreigners, who are temporary resident in China for limited periods of time (Mu, 2022). Adoption might be hindered by privacy issues, as users might fear scrutiny of their transactions. Fullerton and Morgan (2022) argue that the e-CNY could be an effective tool of financial inclusion, if coupled with additional initiatives to tackle rural economic participation.

In terms of inclusivity, the Sand Dollar, the eNaira and the e-CNY are all likely to improve financial inclusion by cutting transaction fees and by increasing access to payment services. The Sand Dollar's is an economic solution to a dispersed population, while the eNaira, among others, has a target to offer an affordable remittance payment corridor to the population groups impacted by the diaspora. The e-CNY represents an advanced, technologically efficient, full payment system. Each of the three CBDCs has objectives related to financial inclusion, but they differ in their models and implementation, due to the specificities of their respective contexts. The Sand Dollar intends to target unbanked and underbanked people, notably on

remote islands (CBOB, 2020c). Digital payments, with mobile access, may alleviate the need for physical cash and traditional banks. The eNaira helps to ease access to financial services for the population living in cities and in rural areas. Access to payment services, through the eNaira wallets, only requires a minimum level of identification and basic devices, improving its inclusivity (Ozili, 2023b). The e-CNY integrates with existing banking networks and payment providers for mass adoption, with the goal of becoming the platform of choice for mobile payments (Huang and Li, 2023). Digital payment systems, such as Alipay and WeChat Pay, represent important players in China, the e-CNY's contribution to financial inclusion is therefore framed in the context of a sovereign digital alternative to private platforms (Huang and Li, 2023). The Sand Dollar, eNaira and e-CNY represent different efforts towards financial inclusion and are influenced by the respective socio-political and economic conditions. While the Sand Dollar's offline capability, the eNaira's mobile availability and the e-CNY's reach to rural areas, are all inclusive measures, additional efforts may be required, to improve the digital literacy levels of the population, by increasing the access to digital devices and by securing transactional privacy. Reforms, technical innovations and user education would support the achievement of the full potential of CBDCs, as inclusive payment systems.

3.1.19. ENVIRONMENTAL IMPACT AND SUSTAINABILITY

The sustainability of the digital transformation and the environmental impact of the electronic devices emerged as a concern, in the context of climate change mitigation efforts. Sustainable finance practices and scalable technologies are key to reduce the world's ecological footprint (European Union, 2025). The future role of cash may be challenged, to emphasise the potential of CBDCs to reduce the environmental footprint of cash issuance, storage, and transport (Lee and Park, 2022). Agur et al. (2022) suggests that CBDCs can be implemented in an environmentally conscious way, if central banks adopt energy-efficient technologies, leveraging existing financial infrastructure. According to research, it may have a lower environmental impact than the physical cash (Lee and Park, 2022). Diverse economic resources and energy policies in the Bahamas, Nigeria and China shape their strategies for CBDCs' sustainability. None of the selected central banks have published evidence of the annual emissions of their platform and their full life-cycle assessments, therefore the analysis is based on assumptions, related to the consumption of the technological infrastructure deployed by the three countries.

The Sand Dollar may have moderate energy consumption, originated by the limited number of transactions, executed on its simple technological architecture. The Sand Dollar deployment is centred on the objective to improve financial inclusion, particularly for

communities that are remote (Wright et al., 2022), rather than on specific greenhouse emission targets, underlining the importance of simplicity and affordability, over high-end environmental sustainability. The CBOB prioritised simplicity over sophistication, lowering costs and consumption of its platform (Kim and Mohan, 2020). The Sand Dollar environmental benefits might be induced by the minimalism of its design, as it uses a permissioned DLT network, with its own dedicated nodes, eliminating the need for high-end computing resources, as transactions are authenticated by a small number of trusted third parties (Branch, Ward and Wright, 2023). The Bahamian environmental policies improved over time, and the Government introduced the Climate Change and Carbon Market Initiatives Bill in 2022 to implement initiatives to support the reduction of overall global greenhouse gas emissions, under the Paris Agreement (Bahamas Ministry of Environment, 2022).

The same considerations made for the Sand Dollar may apply to the eNaira platform, which is based on a private DLT, with a limited number of nodes and reduced computing power required to process transaction, when compared to cryptocurrencies, and with moderate energy consumption assumed. It is possible to assume that its consumption may be impacted by the increase of transactional volumes, in consideration of the number of residents and of the expats interested in the remittance functionality. However, possible ways for the CBN to mitigate the carbon footprint may be to increase the consumption of renewable energy in its datacentres. The Nigerian model illustrates the environmental challenge of developing economies, when confronted with digital finance innovation and limited resources.

The e-CNY runs on a custom platform, with multi-layer security, which runs on a multi-site, high availability infrastructure capable of guaranteeing business continuity and 24/7 services (PBoC, 2021). The centralised system removes the need for expensive consensus algorithms. China's ambitions to be a global leader in digital finance and in environmental management, encouraged the country to introduce laws requiring the utilisation of renewable energy in data centres, with at least 80% green electricity consumption ratio imposed to newly built data centres, at national hub nodes (China National Energy Administration, 2025). While the e-CNY's may require greater energy use than the Sand Dollar or the eNaira, in consideration of the higher volumes processed, China's deployment of renewable power may help to reduce its overall environmental impact.

The comparison assumed different levels of environmental sustainability, based on countries' economic resources, technology progress and policy indications. The Sand Dollar and the eNaira use low-energy DLT technology, with different levels of utilisation and processing volumes. The e-CNY adopts a hybrid platform-based technology that manages high

processing volumes, but China imposes the use of renewable energy in data centres, which may help to offset the carbon footprint. There is still insufficient empirical evidence about the environmental impact of CBDCs, further research may help to ascertain this aspect. The scalability of the CBDCs' solutions should be considered by central banks, to ensure that the environmental sustainability may not hinder their economic efficiency. Authorities may consider introducing a minimum percentage of renewable energy supply to CBDCs' datacentres, particularly for large economies, to mitigate their environmental footprint. Future research should continue to evaluate the long-term environmental impacts of CBDCs and focus on scalability and sustainability of their technological developments (China National Energy Administration, 2025).

Regarding the Sustainability and Inclusivity Dimension, all three CBDCs use tiered KYC to balance privacy and regulatory needs. The Sand Dollar, the eNaira and the e-CNY offer limited anonymity for low-value transactions. Centralised data storage solutions might raise privacy and security concerns, but they may be justified by authorities for their efficiency, crime prevention and compliance. Each CBDC targets financial inclusion but adapts to local contexts. The Sand Dollar's offline capability is vital for inclusivity in island communities, the eNaira's USSD access may be crucial for rural areas in Nigeria, while the e-CNY leverages China's advanced banking intermediaries for users' onboarding and training. All three CBDCs might require ongoing efforts to promote digital literacy in remote rural areas. About environmental impact and sustainability, the Sand Dollar's simple architecture may be considered as low-energy, the eNaira's and the e-CNY's footprint may depend on transaction growth and energy mix used in its datacentres. National policies on the utilisation of renewable energy in datacentres may provide decisive incentives for the reduction of carbon footprints. The comparative analysis of the three CBDCs for this dimension is detailed in the table below.

TABLE 10: COMPARATIVE ANALYSIS OF THE SUSTAINABILITY AND INCLUSIVITY DIMENSION

Dimension	Sand Dollar	eNaira	e-CNY
Privacy	• Tiered KYC: Three wallet tiers including business, with limited anonymity for low-value transactions; higher-value requires full identification. With its tiered KYC, the transaction limits are based on user identification level. • Privacy balanced with AML/CFT compliance. • Potential model for small economies seeking digital inclusion with privacy.	• Tiered KYC: Five wallet tiers including business, with increasing identification requirements. • It complies with national data protection laws. • Entry-level wallets need only phone and National ID Number (NIN), while higher tiers require additional information.	• Tiered KYC: Five wallet tiers including business, with sub-wallets and different privacy thresholds. • Managed anonymity. Basic wallets are anonymised, while large transactions are only authorised in wallets with higher KYC compliance. • Regulatory oversight prioritised for national security. User data accessible in higher tier wallets, for anti-money laundering and crime prevention.
Inclusivity	• Focus on Financial inclusion. • Accessibility and affordability are central. • The Sand Dollar is designed to support unbanked and underbanked people. • Mobile app wallet and SMS. • Supports offline payments, crucial for areas with limited connectivity. • Low transaction fees with minimal barriers to entry. • Partnerships with local businesses and government for daily use (utilities, subsidies).	• Targets informal economy and unbanked/underbanked people. • Compatible with mobile money platforms and works on feature phones, via USSD, with no internet required. • Enables low-cost transactions. • Collaborations with mobile service providers to keep costs low. • Network coverage and digital literacy may be a concern. • Awareness campaigns may improve adoption rates.	• Advanced alternative to private payment apps (Alipay, WeChat Pay). • Online and offline payment capability. • Hard wallets introduced for wearable and IoT devices. • Payment option for foreigners and temporary residents. • Urban areas may benefit more from the advanced tech platform, than rural regions. • Incentives, (for example lotteries and discounts) deployed to increase adoption rates.

Dimension	Sand Dollar	eNaira	e-CNY
Environmental Impact and Sustainability	• Reduced energy utilisation, due to limited transaction volumes and dedicated nodes, which decrease computing needs. • Bahamas' use of renewables may help to lower carbon footprint. • Simplicity and affordability prioritised over high-end sustainability.	• Moderate energy requirements, however, sustainability may be challenged, by growth of transaction volumes. • Carbon footprint may be reduced by increasing renewable energy use.	• Energy-efficient design, but high transaction volumes may increase the total consumption. • China's policies promote renewable energy in data centres may help to reduce its footprint. • Environmental impact may depend on the continued utilisation of renewable energy.

Source: Author's elaboration.

3.2. CONCLUSIONS AND FUTURE DEVELOPMENTS FOR THE COMPARATIVE STUDY OF PRIMARY CBDCs

The three CBDCs demonstrate a combination of objectives, motivations, designs, and diverse approaches across different geographies. Future studies may play a crucial part in establishing CBDCs as a successful payment mean. Recent studies show that CBDCs have potential, but their success require users' trust and regulatory backing (Auer, Cornelli and Frost, 2020). The privacy features require a fine equilibrium between efficient processing of transactions and compliance to regulations. Although tiered KYC models provide a valid approach, to ensure adequate degrees of user anonymity, the impact on end users may depend on the technological solution deployed, and on the regulatory framework applicable to the different privacy scenarios. Researchers stress the importance of open policies, strong data protection regulations and public outreach to improve users' confidence. The design of CBDCs should establish a balance that satisfies both privacy requirements and regulatory demands. The implementation of hybrid data management systems with enhanced cryptographic security, together with comprehensive standard privacy guidelines for CBDCs, may safeguard user data, without creating unwarranted surveillance (Murphy et al., 2024).

Notwithstanding the expected benefits, significant challenges persist. The technological infrastructure remains a limitation for the Sand Dollar and the eNaira, and a specific focus should be dedicated to encouraging user adoption. A CBDC may bolster sovereign control over its currency and domestic payment systems. The interoperability of CBDCs with payment systems may improve the efficiency of transactions, by reducing processing times and costs. The Sand Dollar and the eNaira along with the e-CNY exhibit the unique economic objectives and political goals of their respective countries, while reflecting their technological infrastructure capabilities. The three CBDCs share the common objectives of financial inclusion and payment system modernisation but demonstrate significant variations in their legislative structures, privacy approaches along with regulatory supervision. To achieve full potential in financial inclusion, central banks may need to address several limitations.

The Sand Dollar has regulatory measures designed to benefit underserved communities, complementing physical cash. It enhances national sovereignty over monetary policy, reducing the dependence on external payment networks (CBOB, 2019). The authorities' commitment to the initiative is important to ensure equal access. The Sand Dollar uses a mobile wallet, guaranteeing offline support for remote islands (CBOB, 2020e). The Bahamas implemented a gradual rollout strategy that seeks complementarity of the Sand Dollar to physical cash. Researchers highlight the potential of Sand Dollar to reduce cash usage,

including in locations where it is difficult to access conventional banking (Branch et al. 2025). The Sand Dollar aims at enabling basic peer-to-peer payments and merchant transactions, improving the payment performance in the dispersed region (CBOB, 2020c). Despite the Sand Dollar's initial success, researchers claim that its infrastructural constraints in isolated areas may prevent its widespread adoption (Sisodia, 2024). The Sand Dollar received praises for its balance between privacy and oversight, with transparency to authorities for high-value transactions (Wright et al., 2023). It is a good example of solution for small economies, ensuring financial inclusion and operational resilience, although it may face challenges related to scalability (Wright and Todd, 2024). The Sand Dollar's mobile-first strategy satisfies geographical challenges but relies on a limited infrastructure. The Sand Dollar is currently constrained in terms of programmability, having only basic features, and therefore not being able to support adaptive monetary policy targets. Its limited functionalities originate from the need to ensure easiness of use and accessibility for a variety of people with different levels of technological knowledge, and an intent to preserve simplicity. Its main achievements relate to transaction efficiency and cost reduction for cash management activities. Future perspectives include the possibility of making the Sand Dollar even more functional, developing advanced features, to facilitate government payments and to implement selective subsidies (Branch, Ward and Wright, 2023).

The eNaira was designed to ensure greater transparency across the informal cash-based economy (Ree, 2023). The eNaira supports the government's target to combat financial crime, with laws designed to encourage its use across official financial institutions (CBN, 2021b). State incentives and educational efforts were able to drive the initial adoption, thus highlighting the importance of public trust in CBDC implementation (Idisi et al., 2024). The eNaira's role in monetary policy is still emerging, although some economists believe it will slow down the informal economy, by forcing unregulated cash flows to CBDC transactions (Ree, 2023). The eNaira may allow the CBN to conduct more targeted monetary interventions, for example subsidies for specific segments of the population (CBN, 2021a). By reducing the dependence on cash, the eNaira helps the CBN to keep control on currency flows, improving its ability to contain inflation. The eNaira seeks to balance accessibility and anonymity, while utilising modern technology (Obiora, 2023b). The eNaira acts as a tool that facilitates financial inclusion for populations with low digital literacy skills and significant income differences. However, the eNaira's effectiveness is impeded by the low penetration of the internet, especially in rural areas of Nigeria (Fullerton and Morgan, 2022). The success of the eNaira in achieving mass adoption depends on the improvement of infrastructural challenges and the increase of adoption and usage rates.

China's e-CNY lessens the dependence on private digital money and overseas payment systems, thus bolstering monetary sovereignty (Prasad, 2022). The internationalisation of the e-CNY could alter the dynamics of global financial power. In international trade, the e-CNY could challenge the current status quo (Bencivelli and Zangrandi, 2023). CBDCs provide increased regulatory transparency of transactions to help to reduce money laundering and terrorist financing. However, increased monitoring might present privacy risks. The e-CNY can benefit from China's advanced technology, which enable managed anonymity in Tier-4 wallets (Mu, 2023). CBDCs provide central banks with novel tools for monetary policymaking. In future, the PBoC might decide to apply interest rates directly on wallets (Yang and Zhou, 2022). The e-CNY programmability enables conditional payments, potentially representing a significant tool for monetary policy innovation (Saliya, 2025). Data security is centralised in the e-CNY, allowing control of data flows and transactions. The e-CNY displays the potential to enhance regulatory oversight and compliance over regulations (Lu and Chen, 2021).

CBDCs may help to open the doors of financial services to unbanked individuals. While the Sand Dollar and eNaira aim to expand financial inclusion and to modernise their payment infrastructure in response to domestic issues, the e-CNY has broader goals such as enhancing monetary sovereignty and having an impact on international trade. The Sand Dollar is capable to reach rural areas, where banking facilities are minimal (CBOB, 2020c). By leveraging mobile technology, the eNaira offers to provide financial services to Nigeria's unbanked people (Ogunrinde, 2023). The Sand Dollar, eNaira's and e-CNY present similar approaches to the distribution model, considering country-specific agendas, political contexts, and technology landscapes. Whereas the Sand Dollar and eNaira seek to provide a balance between privacy with financial inclusion, the e-CNY seeks to fully comply to the regulatory framework. The Sand Dollar exemplifies small-scale governance, improving financial inclusion, the eNaira strives for greater transparency in the economy, and more efficient public services. Besides increasing domestic payment efficiency, the e-CNY has wider aspirations of internationalisations, through pilots with Hong Kong (HKMA and PBoC, 2024) and the support for cross-border transactions through the mBridge project (BIS, 2024). These objectives shape how each CBDC may impact financial stability. The effectiveness of CBDCs depends on resolving legal framework issues as well as establishing robust technology infrastructure and public trust. CBDCs must maintain adaptable privacy regulations and control mechanisms to manage new emerging issues effectively. For adoption rates to expand, it will be necessary to implement these improvements. Adequate regulations are necessary to prevent these digital assets from enabling extensive monitoring capabilities.

The insights show that a CBDC's architecture, governance and user interface have a major impact on how it achieves its objectives. The Sand Dollar has mandated the roll out of the Sand Dollar digital wallets to the AFIs, with the oversight by the central bank (CBOB, 2020a). With its balanced approach, the Bahamas' gradual adoption has allowed the Sand Dollar to represent an alternative to complement physical cash (Nguyen, 2024). The Sand Dollar's open design is praised for its accessibility features, reducing the financial gap for targeted groups of population, without intending to phase out cash (Branch et al., 2025). The eNaira seeks to reduce the reliance on cash (Ozili, 2023c) and to distribute responsibilities between the CBN and the authorised financial intermediaries, who work jointly to ensure compliance (CBN, 2021a). The infrastructural concerns of the eNaira were cited as an adoption challenge, demonstrating the importance of an appropriate technological platform (Sadat and Shaba, 2025). China's e-CNY is expected to achieve monetary sovereignty, to limit the influence of private platforms, and to bridge the gap between the different areas of China, ensuring the stability of the economic system (Samek and Vlasta, 2021). The PBoC (2021) centralises the e-CNY management and enables monitoring and oversight, focusing on regulatory compliance and on the gradual substitution of physical cash. The centralised nature of the e-CNY might pose challenges, with authors arguing that it might enable data disclosure (Tronnier and Qiu, 2024).

Whereas the Sand Dollar provides flexibility and embraces inclusivity, the e-CNY illustrates an example of advanced functionalities and large processing volumes. The eNaira deliver a secure and inclusive digital currency, amid technical limitations. The CBOB focuses on limiting the state involvement and on protecting user privacy, within its regulatory framework (Wenker, 2022). This governance model has the objective of building trust and fostering acceptance within the society. While the eNaira enables traceability to reduce the informal economy, the CBN has pledged to safeguard user data, with the objective to reconcile compliance with user privacy (CBN, 2021a). The PBoC has advanced control over the e-CNY, to perform transactions efficiently and to enforce compliance (Branch et al., 2025).

All three countries comply with regulatory mechanisms. China's model is more centralised, while the Bahamas and Nigeria are more moderate in their balance between regulation and user privacy. The CBDCs' environmental impact remained less explored, in comparison to the ecological footprint of private digital money and physical cash management (Paradigm Research, 2024). CBDCs can foster financial inclusion, bringing efficiency and cost savings, but their environmental impact is still unexplored. The implementation of energy-efficient systems may reduce the CBDCs' environmental footprint. The Sand Dollar is underpinned by governmental policies towards digital transformation (CBOB, 2019). The eNaira is one

component of Nigeria's overall economic transformation plan that aims to digitise the economy and to reduce dependence on cash (CBN, 2021a). The governmental support and policy backing are essential for the eNaira ongoing adoption and effectiveness (Ozili, 2023c). The e-CNY reflects China's long-term strategic interests in technological leadership.

Developing digital infrastructure investments, along with interoperability with existing payment systems and reliable connectivity access are important success factors for CBDCs. Wide outreach and educational programs should be developed to help individuals and businesses to gain confidence when using digital financial services. The establishment of solid safety procedures alongside transparent policy structures and consumer protection procedures is fundamental for central banks to build public trust. Regulatory approaches ought to balance the promotion of innovation with risk management strategies. The design of CBDCs by central banks should align with their nation's specific economic requirements as well as its socio-economic conditions and technology level. The analyses of the three case studies may provide policymakers and central banks with an opportunity to improve CBDC designs and implementation projects, to foster financial inclusion and to promote sustainable economic growth.

This chapter highlighted the importance of user privacy, as a key element of widespread adoption. The innovation in CBDC may need to optimise the trade-off between programmability, privacy, and public trust, to enable long-term adoption. The contributions of central banks, financial intermediaries, technology providers and international institutions will be crucial to address these difficulties. Future research may analyse the long-term implications of CBDCs. Cross-country comparisons across multidimensional aspects, and the identification of best practices to attain interoperability, while balancing efficiency, security, and privacy, may represent potential topics of interest for future research.

CHAPTER 4. THE ASSET TOKENISATION PROCESS AND ITS SETTLEMENT IMPLICATIONS FOR CBDCs

Over the past years, the tokenisation process has attracted growing attention from both academic researchers and industry professionals, with scholars acknowledging its capacity to optimise operational procedures, while lowering transaction fees and improving market accessibility and efficiency (Cisar et al., 2025). Specific research questions may investigate what asset tokenisation is, its operational principles, and what are its advantages and challenges. The tokenisation process transforms ownership stakes in financial assets, and physical assets (properties and commodities), into digitally distinct tokens, which may be stored on a Distributed Ledger Technology (DLT) platform by using cryptographic security, alongside programmable smart contracts and decentralised verification methods (Teis and Clarke, 2024). The process extends beyond simple digital reproduction (such as scanning paper certificates), as it involves creating a digital bearer instrument or a registered claim stored on a shared ledger, protected by cryptography (Aldasoro et al., 2023). The concept of tokenisation introduces a transformative change to asset ownership management within the financial system. The process creates a digital version of an asset, which includes its related rights such as ownership or cash flow entitlements, embedded within a digital token that operates on a DLT platform.

Traditional assets that can be tokenised include financial assets, such as public and private equities, corporate and government bonds, as well as derivatives and investment fund shares (BIS and CPMI, 2024). Real assets in scope for tokenisation include commercial and residential real estate and infrastructure projects, along with commodities like gold and oil as well as art and collectibles. Intangible assets may comprise intellectual property rights and carbon credits. The system provides advantages such as fractional ownership, i.e. asset division into affordable units, and it enables rapid settlements with continuous market access, which may improve market liquidity and efficiency (CAIA et al., 2021). Investors may reach easier to access real estate markets, as expensive properties can be split into thousands of tokens that enable continuous peer-to-peer trading (Ebadi, 2025). For tokenised bonds or commodities, the transfer of tokens can be executed through ownership transfer of the asset, while smart contracts may enable coupon payments or commodity deliveries (BIS and CPMI, 2024). The research field has progressed from initial guidelines to detailed empirical studies, through pilot projects such as the European Investment Bank (EIB, 2021) blockchain bond, the Siemens' digitally native bonds (Siemens, 2024), and the SIX Digital Exchange (SDX, 2021b).

According to Rooz (2024), the tokenisation process may represent the next phase of capital market evolution with an expected annual operational saving of USD15 to 20 billion. The World Economic Forum published predictions that up to 10 per cent of global GDP may become tokenised by 2027 (WEF, 2024). The DLT core features of shared record-keeping, immutability, transparency, and programmability may create a potential alternative or complement existing financial market infrastructures such as the Central Securities Depositories (CSDs), payment systems, and traditional exchanges, according to reports from the ECB (2025) and the BIS, SNB and SDX (2020). Traditional systems operate using multiple intermediaries and reconciliation processes must be executed across segregated databases. Tokenisation may introduce a sole source of truth, to allow asset transfers and settlements to happen on the ledger, using cryptographic trust (Cong and He, 2018). The emergence of new technologies has the potential to redefine the financial system; however, without tokenised central bank money, this evolving ecosystem may lack a common, risk-free settlement asset at its core.

Advancements in blockchain and in DLT technologies, have forced traditional financial institutions to reassess their back-office operations, alongside their settlement processes and liquidity management structures (OECD, 2020). The drive towards re-evaluation stems from evidence that blockchain and DLT platforms may automate operational tasks, such as clearing and settlement, thereby enabling significant efficiency improvements (Rooz, 2024). Testing programs and preliminary implementations by exchanges, depositories and banks have increased confidence in the tokenisation process through its practical applications. In fact, the tokenisation of equities, bonds, real estate, and fine art is currently being investigated through projects initiated by banks and large corporations. The European Investment Bank (EIB) became a pioneer, by issuing digital bonds on both public and private blockchains between 2021 and 2024, while startups issued tokenised shares for significant real estate properties. However, the global market size of tokenised assets continues to be limited. As of May 2023, an analysis valued tokenised assets on public blockchains at USD2.15 billion, which represents only a small fraction of the global asset markets (Carapella et al., 2023).

The tokenisation process remains experimental and at early stages, as most initiatives remain in pilot projects or operate within private blockchain networks, according to the Financial Stability Board (FSB, 2024b). Despite current low adoption rates, financial experts (Kumar et al., 2024) predict strong growth of tokenised assets with Boston Consulting Group (2024) estimating that on-chain real-world assets could reach USD16 trillion by 2030. Furthermore, an entire ecosystem of ancillary services has emerged to address tokenised assets' specific demands, through private key custody solutions and regulatory compliance frameworks, alongside cybersecurity measures and risk management systems. The security of private keys

serves as the fundamental element of digital asset custody, which demands targeted methods and technological solutions to protect token holders' ownership rights, within decentralised systems (Kapronasia, 2025b). The application of KYC, AML and data privacy standards, within tokenised assets, requires the development of new compliance technologies and advanced risk evaluation systems (FATF, 2021).

The paper enhances the existing research on financial technology and digital currencies by examining the role of asset tokenisation and CBDCs in financial markets. The key research questions investigate the regulatory and technical considerations for asset tokenisation; the practical applications and pilot projects related to asset tokenisation; what role CBDCs can play in the settlement of tokenised assets; and how do tokenised deposits, stablecoins and cryptocurrencies compare to CBDCs, in the context of asset tokenisation. The lifecycle of digital tokens consisting of issuance, distribution, trading, and settlement, including the automation of various operational processes (such as dividend payments and compliance checks) through smart contracts, is analysed in this paper. This study evaluates technical standards, while exploring token creation processes and their asset linkages. The paper reviews emerging regulatory frameworks in major jurisdictions i.e. the US, EU, UK, Singapore, and Switzerland and it includes case studies of tokenisation projects that demonstrate both successes and failures, exploring how tokenised assets interact with CBDCs, tokenised deposits, stablecoins and cryptocurrencies. The study analyses the requirement for stable and uniform regulations, to support the effective implementation and cross-border interoperability of emerging digital technologies. The combination of CBDCs with tokenisation technologies results in an efficient system for settling digital assets, strengthening liquidity and reliability in new digital markets, according to the BIS, SNB and SIX (2020). The analysis demonstrates that CBDCs can represent a key element to improve settlement processes of digital assets.

This study integrates academic perspectives and recent research findings, to evaluate both the advantages and challenges of tokenisation within financial systems. It delivers an academic and practical overview of the current state of the asset tokenisation process at the time of writing, through a clear and comprehensive analysis. This study examines how tokenisation may potentially improve the financial markets' efficiency, and it investigates how CBDCs may become an enabler and complement tokenisation processes. The analysis encompasses the theoretical foundations of tokenisation, alongside empirical efficiency improvements, and CBDCs' case studies from real-world applications. The paper proposes directions for forthcoming research efforts. The paper offers a comprehensive academic outline of a rapidly evolving field, by analysing recent academic articles, along with regulatory reports and industry surveys. This paper conducts a detailed investigation of the challenges

and future directions for asset tokenisation and a critical assessment of the current research landscape, surrounding the asset tokenisation process and its implications for CBDCs. This paper provides readers with a conceptual overview of asset tokenisation processes, alongside their key components, while evaluating the potential role of CBDCs within the new monetary architecture. The author recognises that present studies fulfilling similar objectives are limited. The study is exploratory in nature, aiming to investigate the relatively new and evolving field of asset tokenisation and its implications for financial markets and CBDCs. The research begins with the review of current literature on the asset tokenisation process and standards, and CBDCs, to understand the potential use cases, the implications and to identify gaps in current knowledge.

The paper includes real-world case studies of countries and financial institutions that have implemented or are in the process of implementing asset tokenisation and CBDCs to formulate generalisations and derive recommendations. Thematic analysis is exercised for examining qualitative data from case studies, identifying recurring themes, and insights. This method helped to gain knowledge on how asset tokenisation interacts with CBDCs, through its specific features, limitations, and future scenarios. The research analysed pertinent studies and the latest research papers from primary literature, authored by academic researchers, based on their journals' rankings in the Academic Journal Guide (Chartered Association of Business Schools, 2024) and from publications of international institutions (e.g. BIS, IMF, FSB, OECD, WB, WEF, etc.) and national monetary authorities.

This research has limitations due to the field's novelty, as researchers, industry actors and policymakers continue to explore this subject, while national monetary authorities along with international organisations regularly release new contributions, leading to frequent developments that could drastically impact the current tokenisation processes and standards, and that may affect the study's conclusions. The research would benefit from a more detailed examination of DLT technology development and its integration with current financial systems. The creation of a tokenised market requires technical developments and the integration with existing payment infrastructure. Further studies on regulatory frameworks for tokenisation and CBDCs may assess specific legal aspects, while pilot projects could provide evidence on the implementation challenges and actual benefits.

4.1. DESIGN ARCHITECTURE

The fundamental principles of tokenisation emerge from research in financial markets, alongside blockchain technology and cryptographic security. The operation of traditional financial markets depends on custodial institutions, clearinghouses and banks for trade validation and asset ownership record maintenance (Agur et al., 2025). Although this structure operates effectively, it demands manual and semi-manual reconciliation steps that prolong transaction settlement to several days and amplify systemic risk.

Through blockchain technology, tokenisation aims to streamline financial transactions, by providing a shared ledger that allows all parties to monitor real-time asset ownership updates (Armas and Singh, 2025). The unique feature of tokenised assets is represented by the ability to interact with smart contracts, capable to operate automatically and to be digitally recorded on a DLT platform. According to Peters and Panayi (2016), smart contracts may enable automated execution of payment flows such as coupon payments on tokenised bonds, along with corporate actions, such as shareholder voting and post-trade procedures.

Tokenisation incorporates operational logic into digital asset representations, to decrease administrative tasks, while reducing human mistakes and allowing rapid settlement processes (OECD, 2025). To work effectively, smart contracts depend entirely on the reliability of both their code and their connection to external data feeds, known as oracles, according to Cong and He (2018). Smart contracts that run automatically, may spread operational errors, if they receive flawed information from oracles, due to technical failures or malicious interference. Regulatory clarity presents other major concerns, in fact, legal systems established for traditional contexts may encounter difficulties both in enforcing and in interpreting code-based obligations, when disputes such as contested asset ownership and breach of contract claims occur (OECD, 2020).

Despite the notional foundations that support disintermediation and automation potential, real-world advantages of this innovative technology entirely depend on technological stability and appropriate legal and regulatory structures. Implementing tokenisation requires a series of essential steps which must consider both technical aspects and legal requirements. The steps required for the tokenisation of the assets are summarised in the next table.

TABLE 11: KEY PHASES AND CRITICAL ACTIONS FOR THE ASSET TOKENISATION PROCESS

#	Phase	Detail	Critical Actions
1	Asset Selection and Legal and Regulatory Framework	The process demands identification of the asset and precise definition of token rights, while establishing legal robustness and enforceability within relevant legal jurisdictions.	• Experts need to determine under the law, whether the token qualifies as a security, a commodity, a utility, or falls into another category. The applicable regulatory framework depends on this definition (BIS and CPMI, 2024). • The legal claim to the underlying asset remains permanently connected to the digital token. The connection between the digital token and the underlying asset necessitates the use of legal wrappers or special purpose vehicles (SPVs), along with specific contractual agreements. • Protection measures must be implemented to secure token holder claims, when the issuer or platform operator becomes insolvent.
2	Platform Choice	The selection of the foundational DLT determines the attributes of the tokenisation project.	• Public/Permissionless Ledgers (e.g. Ethereum, Polygon) provide transparency and access to data, with their decentralised governance, however they struggle with expansion capabilities as well as transaction expenses and data exposure, since transaction data remains visible to the public. • Private/Permissioned Ledgers (e.g. R3 Corda, Hyperledger Fabric) are eligible for institutional applications, as they select access to participation and validation of transactions, directing data visibility (Brown, 2019). Permissioned ledgers can provide greater scalability, yet they may create isolated systems, and they may depend on the rules set by the controlling consortium for governance. • Standards applicable to fungible (ERC-20) as well as to non-fungible (ERC-721) tokens (Vogelsteller and Buterin, 2015; Entriken et al., 2018).
3	Token Creation	Smart contracts serve as automated rulebooks which oversee the management of tokens.	• Identification of token characteristics. supply (fixed/variable), divisibility, transferability rules. • Smart contracts may automate processes for distributing dividends and interest payments, while executing corporate actions such as voting and ensuring regulatory compliance by checking investor accreditation and geographical restrictions along with holding periods. • The token lifecycle management includes issuance, followed by trading activities, until reaching redemption or expiry. • The permanent nature of blockchain technology makes it challenging to fix smart contract coding flaws after creation, as the code dictates the rules, which makes rigorous pre-deployment audits essential (this represents also the reason why errors may become costly).

#	Phase	Detail	Critical Actions
4	Issuance and Distribution	Security Token Offerings (STO) function as digital native versions of standard securities issuance, when using DLT technology (Park et al., 2024)	• STOs differ from the Initial Coin Offerings (ICO) because they operate under specific regulatory requirements. • STOs operate under existing securities regulations, which require prospectus disclosures and investor suitability evaluations, through KYC/AML processes, alongside marketing law compliance.
5	Trading and Settlement	Tokenisation aims to improve the settlement processes. New trading platforms built on DLT, also known as Security Token Exchanges or Automated Market Makers (AMMs), are developing to serve markets that operate 24/7 and feature alternative trading structures.	• The primary objective of tokenisation is to accomplish atomic settlements, through simultaneous Delivery versus Payment (DvP) for assets and Payment versus Payment (PvP) for currencies within one or multiple interconnected ledgers. • This approach effectively mitigates principal risks, where one party delivers assets but fails to receive payment, and removes counterparty credit risk found in traditional T+2 or T+1 settlement cycles. • A dependable digital payment mechanism on either the same or an interoperable ledger system is essential for true DvP settlements. • A reliable digital payment leg for DvP settlement could consist of a CDBC, a tokenised commercial bank deposit or regulated stablecoin, as identified by the BIS and CPMI (2024). • The integration between DLT platforms and traditional payment systems may risk creating temporal delays and potential execution risks.

Source: Author's elaboration.

Academic researchers and policy makers have taken a strong interest in the development of asset tokenisation technology. Academic discussions frequently revolve around the potential benefits of tokenisation, regarding the liquidity enhancements for assets, which traditionally lack liquid markets. CAIA et al. (2021) explain that fractionalisation and continuous digital markets may help to decrease transactional frictions and to create new investment opportunities. The research by MAS (2020) clarifies that tokenisation reduces liquidity premiums, by shrinking minimum investment thresholds and creating global market access, which may result in decreased capital costs for issuers. Despite limited empirical evidence, due to the current initial phase of asset tokenisation, researchers have evidenced only minor liquidity advancements on the analysed platforms. Ebadi (2025) conducted a study which examined the tokenised real estate platform. Token markets displayed automatic adjustments of bid-ask spreads, according to supply and demand, with an immediate price discovery process, although having lower absolute liquidity, indicating potential efficiency gains.

Despite the potential benefits of the investment fractionalisation, some academics pointed out that the fractionalisation would not be able to ensure liquidity, without the support of other concurrent factors. According to a report from the OECD (2025), although tokenisation can increase liquidity, by using automated market makers and extending access, various markets may become fragmented, when they operate on different platforms or standards. The trading activity of tokenised assets remains restricted, as they primarily attract specialised groups of investors. Tokenised assets need institutional market makers or major exchange integration to achieve significant liquidity (WEF, 2025). The BIS and CPMI (2024) projected that combining tokenisation with CBDC may enhance liquidity, by merging existing isolated market structures into unified infrastructures. Aldasoro et al. (2023) argued that the increase in token platforms might create fragmentation, as multiple independent token systems may lead to liquidity fragmentation in each platform. The academic debate centres on conditions for liquidity benefits, as tokenisation diminishes technical trade barriers, however, attaining market liquidity requires investor interest, alongside regulatory transparency and either trading platforms consolidation, or interoperability across new platforms and legacy payment systems.

Tokenisation may enable wider accessibility to investment opportunities for diverse investors. Through fractional ownership and accessible digital platforms, average investors may gain access to commercial real estate, fine art, and venture capital investments, previously reserved to wealthy individuals and institutions, according to CAIA et al. (2021). Retail investors can create diversified portfolios, by acquiring a limited number of tokens in infrastructure projects and private equity deals, which may boost their diversification and potential returns. However, there may be barriers to the process of democratising wealth management practices. The regulatory restrictions applied to tokenised offerings, across several jurisdictions, impose access limitations to accredited or qualified investors, deferring the possibility of a wider participation to tokenised markets, until the regulatory frameworks will evolve. Other constraints are related to financial literacy and operational risks. Providing access to retail investors to new asset opportunities can lead to their exposure to complex risks, that they might not fully understand, including volatility and illiquidity. The initial coin offerings of cryptocurrencies during the preliminary unregulated period of the mid 2010s, serve as an eloquent example of how eliminating financial barriers, can lead to retail savers investing their funds into early-stage ventures, potentially falling into scams, demonstrating that barriers may be important for protecting consumers. Investors who can least afford to take on risks, might face heightened exposure, as tokenisation reduces entry barriers, but currently lacks sufficient disclosure and educational support. Economists have theorised that tokenisation might support small businesses in securing funding from worldwide investors (Chaintech, 2024) and may potentially provide expat groups with opportunities to invest through tokens in

infrastructural projects in their home countries, however legal challenges might remain still valid. Furthermore, the World Bank's bond-i pilot project (World Bank, 2019) has led to discussions about the potential role of multilateral institutions, in creating token markets for development projects, despite the tokens being sold to traditional institutions.

4.1.1. ELIGIBLE ASSET CLASSES

All assets bearing ownership rights can potentially be converted into digital tokens. The representation of different asset classes on-chain requires unique considerations, which determine the benefits achievable from the tokenisation. This section explores the application of tokenisation across major asset categories such as real estate, commodities, equities, bonds, intellectual property, and collectibles along with various financial instruments and provides examples of relevant projects and platforms used.

The application of tokenisation in real estate emerges as a priority since properties represent high-value assets that tend to be illiquid. Through real estate tokenisation, large properties like commercial buildings or resorts can be split into multiple smaller tokens which enables fractional ownership (Businesswire, 2020). Fractionalisation opens property financing to smaller investors who may have access to real estate deals that were previously inaccessible. It can also potentially enhance liquidity. Selling a large building involves complex processes that take considerable time, while trading a token that represents fractional ownership of that building may be conducted through a simple DLT transfer, through secondary market transactions. The tokenisation of real estate typically requires establishing a special purpose vehicle (SPV), or trust, to hold legal ownership of the property and to issue tokens that represent ownership stakes or financial rights in the SPV (Kreppmeier et al., 2023). Token ownership may grant access to rental income shares and sale proceeds revenues, while allowing governance control in property management. The Aspen Coin in 2018, represented an early real estate tokenisation instance, when the St. Regis Aspen Resort in Colorado used a security token offering, to tokenise part of its operations. Accredited investors purchased Aspen Coin tokens under USA Regulation D, to obtain hotel ownership equity before the tokens became available for trading on the registered platform tZERO in 2020 (Businesswire, 2020). This allowed the investors to gain liquidity from their private real estate investment. Starting in 2019, RealT began tokenising multiple single-family rental properties across the USA, using the Ethereum blockchain. RealT distributes ERC-20 tokens representing properties through individual LLCs, and it distributes rental income to token holders in stablecoins (Moriarty, 2023). The model allows investors globally to buy fractional ownership in rental properties, with clear cash flow visibility, which used to be difficult for cross-border

investors. These projects face legal complexity as each token requires defined legal rights and must adhere to securities and property laws. Despite the challenges, major real estate companies have assessed their capabilities within this domain. The automated nature of smart contracts accelerates property transaction completion, by eliminating lengthy escrow and title transfer processes, while enabling property ownership registries, to be monitored transparently through ledgers. Financial institutions stand to gain from the ability to easily accept tokenised property shares as collateral, while smart contracts enable immediate foreclosure execution in default scenarios (Lewis, 2023). Regulatory adaptation remains a necessity before widespread adoption occurs, because numerous legal jurisdictions continue to mandate notarised property deeds, alongside traditional paper-based land registration systems. A token can depict a contractual claim, while remaining unrecognised as a title transfer, until there are legislative changes. Certain nations, including Liechtenstein, have revised their legal codes to acknowledge tokenised securities and assets (Government of Liechtenstein, 2019), while other countries remain in the process of making similar legal adjustments. As pilot projects continue to develop real estate tokenisation, this process may transform property investment markets, by expanding accessibility and liquidity, depending on the evolving maturity of regulatory frameworks.

The process of commodity tokenisation consists of issuing digital tokens that represent ownership of physical commodities, including gold and agricultural products. The use of warehouse receipts and commodity warrants to trade ownership of commodities has been an established practice. Tokenisation offers a more flexible, efficient approach, as it enables the representation of physical assets, such as gold, which investors can trade or use in decentralised finance applications, for operations such as lending or collateralisation. Precious metals represent a primary area, where successful examples emerged. Gold-backed tokens are available in the market including Pax Gold (PAXG) and Tether Gold (XAUT) as prominent models. Every PAXG token represents an ounce of gold that meets the London Good Delivery standard and is stored in Brinks vaults, with the added benefit that holders can request physical gold delivery, upon accumulating sufficient tokens (Paxos, 2024). Gold-backed tokens provide investors with an opportunity to engage with commodities markets without physical storage, while offering continuous trading availability on DLT platforms. Storage and quality complications may limit tokenisation of agricultural and industrial commodities, however private consortia have used the platform Hyperledger Fabric, to conduct tokenisation experiments with copper and soybeans for supply chain provenance tracking and financial token creation.

The primary advantage of commodity tokens lies in their capability to deliver instant settlement, while decreasing the dependency on major commodity exchanges and intermediaries. Ethereum allows gold token transfers to complete in minutes, unlike traditional gold markets, which require days for delivery or unallocated gold account settlements (Paxos, 2024). Moreover, tokens can enable the integration with smart contracts. A borrowing protocol may allow users to take loans, by using gold tokens as collateral, merging investment in commodities, with decentralised financial technology. Several institutions are investigating the use of tokenisation for supply chain finance, which may include converting warehouse receipts for metals stored at LME warehouses into digital tokens, to facilitate easier pledging and trading across multiple financing deals, while avoiding duplication risks (CAIA et al., 2021). A specific case was represented by the Perth Mint Gold Token (PMGT), launched by Australia's Perth Mint, where each token was linked to a GoldPass certificate, backed by the Perth Mint (2023) effectively transferring government-guaranteed gold assets to the public DLT space. Carbon credits and renewable energy certificates may enter the digital realm through tokenisation and are sometimes considered as commodities in the energy sector. Through projects on Ethereum and Tezos, companies can purchase carbon credit tokens to reduce their emissions, while enhancing market transparency (Toucan Protocol, 2025). Tokenisation may turn fragmented over-the-counter credits into standardised assets that facilitate global trading platforms.

The process of tokenising equities produces digital tokens, which serve as representations of company share ownership. BX Digital (2025) indicates that this method applies to both private equity, which consists of private company shares and funds, as well as public stocks that include shares of publicly traded companies. Tokenised equities may provide more efficient trading options beyond regular market hours, while enabling fractional ownership of expensive stocks and allowing issuers to connect directly with worldwide investors, without relying on conventional intermediaries. The tokenisation concept has started to gain traction in the private equity and venture capital domain. Startups have executed Security Token Offerings (STOs), to sell digital tokens that stand for equity interests or rights to revenue shares (Park et al., 2024). Technology startups have investigated the tokenisation of shares to deliver liquidity to investors and employees before their Initial Public Offering (IPO). The primary distribution method for these tokens involves private placement exemptions, which allows them to be traded exclusively on dedicated security token platforms. Token trading provides investors with liquidity without the need to wait for an IPO, or an acquisition, while companies gain easier access to a broader group of investors, including those from outside their country (Carapella et al., 2023). The regulatory compliance burden remains significant because tokens may be limited to eligible investors, while transfers need authorisation to prevent illegal

resales, which reduces the free trading benefits, unless issuers register their tokens with regulators. Direct tokenisation of public equities confronts greater challenges, due to the need to work within established public markets and regulatory frameworks. There have been initiatives to develop digital tokens, which track the financial performance of publicly traded stocks. One approach has been to utilise tokenised depository receipts. Financial intermediaries such as brokers or trusts, retain real shares from listed companies and provide tokens, which represent claims to these shares. After issuance, holders of these tokens can use authorised exchanges to trade them. Users were able to purchase fractional tokens of tokenised stocks, after the Binance exchange initiated tokenised stocks for various companies. The launch of tokenised stocks by Binance drew scrutiny from regulatory bodies across different jurisdictions including the Federal Financial Supervisory Authority (BaFin), which in Germany alerted about these potential unregistered securities, resulting in Binance halting the service after several months (BaFin, 2021a). The cryptocurrency exchange FTX provided tokenised stock trading, through its collaboration with CM-Equity (Paz, 2021), but experienced uncertainty following its collapse in 2022, which revealed counterparty risks, as token holders needed assurance that CM-Equity possessed the actual shares. Traditional entities have also made progresses. In 2023, Société Générale launched a pilot program to issue digital green bonds on the public blockchain (Société Générale, 2023), while Nasdaq called for regulatory clarity to enable support for tokenised stocks (Nasdaq, 2025). Tokenised equities provide the benefit of rapid settlement timelines, when compared to traditional exchanges, which settle transactions over two or more business days, as token transactions complete in minutes, facilitating trading opportunities outside regular hours and creating worldwide access for small investors. Fractional ownership allows investors to purchase tiny sections of a USD3,000 stock, which opens new micro-investment opportunities, while democratising wealth management practices. Automated smart contracts may enable direct dividend payments to token holders' wallets, providing shareholder voting mechanisms through on-chain governance tokens. These developments have the potential to lower the administrative overhead tasks. Issuers that use tokens for representing shares could benefit from a simplified management of capital structures, while also reaching a wider investor base, as shown by initiatives like ArCoin, which enabled digital subscription to tokenised mutual fund shares (Arca, 2023). Equities operate under the most stringent regulatory frameworks. Securities laws heavily regulate share transfers of public companies in most jurisdictions and require alternate trading systems to obtain licenses (Park, Lee and Kim, 2024). The mapping of token ownership to shareholder rights requires legal custodians or nominees, to ensure that companies may recognise token holders as shareholders of record. Private equities and funds may receive tokenised assets through exemptions, before being traded within closed networks, to increase liquidity for traditionally illiquid assets.

However, public stock tokenisation remained pilot-based or under strict regulatory scrutiny. Most experts agree that tokenisation may initially develop in private markets, due to their prominent levels of inefficiencies, before spreading to public markets when legal frameworks adjust (McKinsey, 2023).

Enterprise blockchain pilots have consistently targeted the bond market, since bonds offer substantial potential for operational improvements, from issuance to post-trade activities. The concept of tokenised bonds encompasses the digital representation of debt securities including government and corporate bonds. Representing debt securities as digital tokens leads to a streamlined process for distribution, alongside coupon payments and secondary trading operations (Roland Berger, 2023). Many high-profile projects have demonstrated bond tokenisation on both public and private ledgers. For instance, in 2018, the World Bank introduced the bond-i, as a USD110 million two-year bond which operated on a private Ethereum-based blockchain platform, and it was developed alongside Commonwealth Bank of Australia (World Bank, 2019). This was one of the earliest examples of a legally binding bond, issued via distributed ledger, and it showcased automated bond lifecycle management (World Bank, 2019). In April 2021, the EIB issued EUR100 million worth of 2-year digital bonds, through the public Ethereum blockchain in a transaction led by Goldman Sachs, together with Santander and Société Générale (EIB, 2021). The bond tokens were purchased with traditional fiat currency by investors, while the settlement transaction between the underwriters and the EIB used an experimental wholesale CBDC from Banque de France which represented tokenised central bank money (BdF, 2021). The Ethereum token contained the bond details and Société Générale's blockchain division, Forge, served as on-chain custodian and settlement agent (Société Générale, 2024). In 2022, the EIB released a EUR100 million bond, through Project Venus, on a private blockchain using Goldman Sachs' GS DAP tokenisation platform, while receiving a tokenised euro CBDC from Banque de France and Banque du Luxembourg for delivery-vs-payment (EIB, 2022). The bond settlement occurred immediately (T+0) and marked the first-ever cross-chain atomic swap, between a CBDC token and a security token. The DLT platform demonstrated its capability to manage a syndicated bond issuance and its settlement processes, under both French and Luxembourg legal frameworks, in an experimental market environment. In 2020, the Thailand's government launched a blockchain-based savings bond program, built on the permissioned Hyperledger platform that sold USD1.6 billion worth of bonds to its citizens, through a mobile application, to demonstrate how tokenisation can broaden retail access to government debt (IBM, 2020b). In 2021, the Swiss Digital Exchange (SDX) launched a CHF150 million digital bond that operated, comprising two exchangeable parts, on both SIX platform for conventional trading and SDX's DLT for tokenised trading, and achieved full fungibility between these platforms, to

bridge traditional and digital bond markets (SDX, 2021b). The advantages of tokenising bonds may be compelling. Issuance can be faster and automated, as the use of smart contracts to encode bond terms may reduce extensive manual paperwork requirements, during bond syndication and registration processes. Tokenised bond distribution reaches broader audiences, because issuers can connect directly with investors through online platforms, instead of broker networks, although major bond issuances still require bank involvement, as shown with the EIB case (EIB, 2021). Traditional bond settlement processes require two business days or more to complete, particularly across international borders needing multiple custodians, while token-based transactions can achieve instant delivery versus payment, if both assets share the same or interoperable ledgers. The necessity for intermediaries such as clearing houses and settlement failure risks can be minimised, if tokens may achieve real-time atomic settlement (FSB, 2024b). Smart contracts may ensure coupon outflows, by automatically triggering scheduled payments to token holders, using digital currency to manage corporate actions, such as early redemptions or interest calculations, without human intervention. The reduction of operational manual tasks enables 24/7 continuous trading activities of tokenised bonds in secondary markets, and automatic peer-to-peer transactions, which is beneficial for liquidity, especially for small bond issues. However, challenges persist, as the achievement of regulatory acceptance remains a crucial step, with numerous initiatives currently operating only as sandbox or as part of pilot projects. Market operators would be required to promote awareness campaigns, to bring investor acceptance levels of digital wallet bond holdings, in line with the acceptance levels of the traditional custodian banks' model. Also, integrating tokenised bonds, with existing market infrastructure is non-trivial, institutional investors may only access trading platforms that successfully integrate with their established internal systems, thus limiting their operations. Since 2023, the EU's DLT Pilot Regime permits licensed venues to conduct DLT-based trading of bonds and stocks, under a regulatory sandbox, embracing financial innovations (European Parliament, 2022; ESMA, 2022). The evolution of technology and legal frameworks may support the issuance of sovereign bonds (treasuries) as digital tokens, with national monetary authorities investigating the possibility to support financial systems, operating on a unified or interconnected ledgers, integrating CBDCs with tokenised securities (BIS and CPMI, 2024).

While it is possible to tokenise intellectual property assets like patents and trademarks, this sector remains undeveloped, when compared to the tokenisation of other assets. Intellectual property may be tokenised in either Non-Fungible Tokens (NFTs) or distinctive tokens that establish ownership or specific rights. Tokenisation may create innovative revenue streams for copyrighted works, such as music and art, as artists may grant token holders access to future royalty payments from their work, creating a new marketplace, where royalties can be

exchanged (Tian, 2024). The idea has been demonstrated through platforms like Opulous.org, which allows investors to purchase song tokens that provide them with a share of streaming revenue percentages (Opulous, 2025). Similarly, film and media IP has seen token experiments, with projects funding film production through token sales, offering future profit shares to investors (Mathur, 2025). The tokens function as tradable assets which provide liquidity to traditionally illiquid long-term investment opportunities. Tokenisation helps to streamline transactions and licensing processes for intellectual property rights, such as patents and trademarks. An NFT could represent the ownership of a patent, while smart contracts may manage licensing rights and may automatically ensure that only the NFT owner receives licensing rights and collects fees. The concept of IP marketplaces represents an evolving trend, enabling easier transactional processes for buying, selling, and fractionalising patents (Spangenberg, 2023). The transition to this system has progressed slowly, due to the difficulty in both valuing and transferring patents, which require legal assignments beyond token ownership. Digital-art NFTs present a unique case at the intersection of intellectual property and collectibles because they provide a distinct ownership claim to the original digital asset, although copyright transfer requires explicit terms. Certain NFTs reached enormous market valuations, which demonstrated that tokenised IP and digital scarcity can be appreciated by financial markets (Schwiderowski et al., 2023). The inclusion of licence terms and unlockable content for the owner demonstrates how the process of tokenisation enables the integration of rights into digital assets. Ethereum platforms through ERC-721 and ERC-1155 standards served as fundamental infrastructure for issuing NFTs across art, music as well as domain spaces such as Ethereum Name Service names (Entriken et al., 2018). Intellectual-property tokens such as NFTs, frequently use metadata links to connect to digital files and rights descriptions, while also incorporating smart-contract features that manage royalties. The ERC-2981 extension enables automatic royalty payments to the initial creator of an NFT, during every subsequent transaction. The introduction of automated royalty systems, through ERC-2981 NFTs, benefits IP creators by providing a mechanism for ongoing payment, which has proven difficult to enforce in physical art markets (Fekih et al., 2023). Several jurisdictions are currently evaluating whether to legally recognise automated-royalty systems, in fact, tokenising IP requires careful legal review. The purchase of a book NFT may not automatically grant publishing rights which means token offerings need to specify exactly what rights buyers receive. Legal uncertainty arises, when fraudulent activities or mistakes lead to two or more distinct tokens asserting ownership over identical IP assets, as legal authorities must establish rightful ownership. NFTs represent a key instrument that achieved significant success in digital art and media, by creating liquidity and expanding global market access for creative professionals. The emergence of legal systems that acknowledge token records in copyright registers might enable IP markets to function like financial markets with

fractional ownership of patents and copyrights, which might distribute revenue automatically (Schwiderowski et al., 2023).

The emergence of NFTs has positioned collectibles as the widely recognised example of tokenisation for the public. The collectibles term encompasses objects such as artwork, sports cards, postage stamps, aged wines, luxury products, and any distinctive asset that collectors gather and exchange. Digital items such as digital art and virtual trading cards exist in a digital format, while the token serves as proof of ownership and authenticity for these items. NFTs represents digital assets, where every token stands as a distinct entity. The tangible item is paired with a token, which serves as proof of ownership that allows full rights to one holder, or divided ownership among several token holders. NFT tokens were initially issued via ERC-721 tokens on Ethereum (Entriken et al., 2018) and were subsequently issued on other blockchain systems such as Solana, Flow and Tezos. The NFT marketplace saw growth reaching sales volumes exceeding USD25 billion throughout 2021 (Howcroft, 2022). This demonstrated a clear product-market fit for tokenisation. Blockchain technology introduced scarcity and verifiable provenance to digital items that were originally easy to replicate and turned them into collectible assets. The process of tokenising physical collectibles requires secure storage for the item, while circulation of a token represents complete or partial ownership rights. One example is tokenised fine art, with the company Masterworks that created fractional investment opportunities in paintings, through a business structure that owns artwork and distributes ownership shares to investors (Masterworks, 2022). Masterworks sold investment shares in artworks from artists such as Banksy or Picasso, while operating under USA Regulation A, allowing investors to trade these shares on their platform (Kazakina, 2022). Through tokenisation investors can purchase ownership of rare wine bottles held in secure vaults, and either redeem tokens for the physical product or sell tokens to another collector. Several experiments have been conducted to tokenise luxury items like sneakers, watches, and handbags. Startups created digital assets by storing high-end sneakers in secure vaults and initiated a system that allowed people to trade these sneakers as stock-like tokens, which mirrored streetwear resale market prices. Through physical-to-NFT redemption systems, platforms (e.g. 4K.com) can enable users to exchange physical collectibles for NFTs, which people can then trade, while allowing the NFT holder to claim the original item. Tokenisation brings liquidity to illiquid collectibles. While rare baseball cards or art pieces usually demand auctions or private deals for exchange purposes, tokenisation enables their trading within minutes. Investors can acquire fractional ownership of a famous painting through tokens and obtain a portion of a classic car with investment amounts as small as USD100, while still enjoying its value appreciation, without needing large sums of money. These platforms deliver clear ownership records which are vital for art and collectibles

because provenance establishes both authenticity and ownership history. DLT ledgers can assist in tracking an item's provenance from its creation, but authenticating the item during the tokenisation remains necessary. Trust and custody continue to be primary concerns because the value of a token depends entirely on the custodian, who safeguards the physical asset. Should the vault company face failure or fraudulent behaviour, the associated tokens would lose all value. Another research question is related to the difference between collector value vs financial value, as fragmenting collectibles into shares may weaken the intangible sense of ownership pleasure, which contributes to their worth (Kleine, Peschke and Wagner, 2024). The NFT market showed significant instability with numerous digital tokens losing value after the initial hype phase ended, which brought concerns about their future worth. The regulatory authorities maintain caution towards fractional tokens, as they typically resemble investment products. According to regulations in USA, selling shares of a painting creates an investment contract, which necessitates adherence to rules, as demonstrated by Masterworks' choice to use the USA Regulation A framework (Kazakina, 2022). Although numerous difficulties exist in this field, the collectible tokenisation sector remains prosperous and stands out as a gateway introducing people to tokenised ownership concepts. Future developments could demonstrate increased convergence, for example through the merging of NFT marketplaces with auction-house procedures.

A wide range of financial instruments may be suitable for tokenisation, including derivatives and structured products as well as investment funds and collateral. Any valuable financial asset can be transformed into a token, enabling innovative trading methods or usage options. The tokenisation of investment funds (e.g., mutual funds, ETFs, private funds) or shares, increases their accessibility to investors. Through tokenisation, the fund units or shares can be ready for digital wallet integration and subject to quicker transactions, without altering the regulated nature of the security, according to the SEC (2024). Crypto companies have introduced tokenised index funds and portfolios, where investors can purchase a single token that embodies a collection of cryptocurrencies or stocks which are managed outside the blockchain but represented as tokens on it. The ERC-20 tokens usually form the structure of these funds, which follow an index algorithmically, and sometimes use underlying assets managed with smart contracts. Regarding private funds, the ADDX platform in Singapore lists tokenised units from private equity funds, which enables investors to start with smaller minimum investment amount and trade those units in a secondary market, unlike traditional limited partnership models (ADDX, 2022). Financial derivatives, such as a futures or option contracts, could be transformed into an NFT or fungible token format, where smart contract technology may automate the payout process. Banks have explored issuing structured notes as tokens, for example, UBS showed the capability to issue structured securities, whose

returns depend on an equity index, while delivering the note as a token with automated coupon payments and redemption processes (UBS, 2025). Assets represented as tokens in repo and securities-lending markets, provide more straightforward transfer and reuse options. On Corda, the HQLAx produces tokens that represent high-quality bond baskets, which banks can exchange without physically transferring the bonds (HQLAx, 2024). This form of tokenisation functions as a financial instrument, because it represents exclusive asset entitlements. The financial sector is seeing the emergence of tokenised insurance policies, which can function as NFTs for trading or collateral purposes, along with tokenised certificates of deposit and bank notes, and pilot projects with tokenised loans. Real-World Assets (RWA) describe the combination of traditional finance with blockchain technology, and this approach has become popular as crypto investors seek earnings that are not linked to crypto markets and issuers target better funding solutions.

The tokenisation process allows funds and pooled investments, to simplify investor onboarding procedures and to achieve potential worldwide distribution capabilities. Smart contracts provide potential enhancements to derivatives settlement and lifecycle management systems, which become especially beneficial for handling complex payoffs. When converted to digital form, fiat currency serves as a major financial tool that interacts with every other digital asset in the form of CBDC, stablecoins and tokenised cash. Stablecoins, such as Tether's USDT (S&P Global, 2024b), and Circle's USDC (S&P Global, 2024a), have reached a market capitalisation of approximately USD284 billion on 23 October 2025 according to CoinMarketCap (2025a), and represent an example of the tokenisation of fiat money. Stablecoins serve as a fundamental asset in the trading process of tokenised assets. The financial industry is beginning to tokenise bank deposits, as demonstrated by the Kynexys Digital Payments solution, which serves as an internal tokenised bank deposit for corporate clients, according to JP Morgan Chase & Co. (2025). Cash tokens such as stablecoins, tokenised deposits and CBDCs may form the essential infrastructure, to support transaction capabilities for tokenised assets.

The tokenisation may become a unifying solution to decrease friction across multiple financial activities, such as fund share transfers, bond trade settlements, and loan collateral postings by standard digital platforms.

4.1.2. PLATFORMS SUPPORTING ASSET TOKENISATION

The selection of the most suitable platform for asset tokenisation depends on three factors, namely the type of asset being issued, the inherent regulatory requirements for the asset, and the issuer's distribution strategy, whether it aims for broad distribution or controlled issuance. Public blockchains such as Ethereum, Stellar and Tezos provide openness and interoperability, together with access to a broad base of investors and developers, making them ideal for retail-focused and global token markets (like NFTs and security-token offerings). The operation of the blockchains depends on community standards and public consensus, leading to reduced central control, and uncertainty in performance (FSB and IMF, 2024a). The private platforms Hyperledger Fabric and Corda deliver customised solutions for consortia and institutions, which focus on governance principles, ensuring privacy protection and integration with current financial system. These networks lose public accessibility advantages, but achieve better compliance with legal standards, as all participants and validators undergo a vetting process. Both public and private approaches are actively used in tokenisation projects, and there have been hybrid cases that combine the benefits of both approaches, such as institutions implementing permission layers on public blockchain networks, through specific mechanisms (e.g. whitelisted ERC-20 tokens), while consortia assess suitable methods to integrate public liquidity pools. Each blockchain platform implements its own specific token standards or conventions (BIS and CPMI, 2024). The overview of the blockchain platforms for asset tokenisation is available in the next table.

TABLE 12: PLATFORMS FOR ASSET TOKENISATION

Platform	Type	Key Features	Compliance and control mechanisms	Applications
Ethereum	Public	• Leading platform for token issuance. • Smart contracts enable creation/management of tokens for nearly any asset. • Broad developer base and interoperability. • Fungible (e.g. ERC-20), non-fungible (e.g. ERC-721), security tokens. • Developed to support retail and global token markets. • Address scalability and privacy with continuous	• Permissionless structure. • Smart contracts and off-chain processes deployed to achieve compliance. • Advanced standards available, such as ERC-1400 and ERC-3643.	• Security tokens. • PAX. • Gold NFTs.

Platform	Type	Key Features	Compliance and control mechanisms	Applications
		upgrades (e.g. Proof of Stake, Layer-2).		
Stellar	Public	- Fast to deploy platform, with low-cost transactions. - Built-in token creation (no need for custom smart contracts). - Trustlines and decentralised exchange (DEX). - Suitable for payments and micro-investments.	- Require Authorisation flag for KYC. - Clawback feature for asset recovery. - Stellar Ecosystem Proposals (SEPs) deployed for compliance. - Account flags for transfer approval.	Franklin Templeton tokenised money market fund.
Tezos	Public	- Proof-of-Stake verification method for transactions. - Protocol upgrades managed through on-chain governance. - Smart contracts supported. - Multi-asset support for fungible and non-fungible tokens.	- Adaptable standards. - Custom contract logic for restrictions.	- tzBTC (Bitcoin-backed token). - Real estate and art NFTs.
Hyper-ledger Fabric	Private	- Permissioned, modular architecture. - Chaincode for smart contracts. - Privacy features. - No native cryptocurrency. - High transaction throughput. - Integration with enterprise identity systems.	- KYC/AML compliance ensured. - Channel architecture for privacy. - Confidential data collections. - Token SDK for standardised token management.	- Trade finance platforms e.g. we.trade - Syndicated loans tokenisation.
R3 Corda	Private	- Distributed ledger technology (DLT), not a traditional blockchain. - Data shared only with involved parties. - Legal agreement alignment with financial contracts. - Suitable for financial sector applications.	- Permissioned network. - Participant roles (issuer, owner, observer). - Fungible and non-fungible token ledger states - Token SDK with templates. - Consortium governance (incl. Banks and governing body).	- HQLAx (collateral exchanges). - SIX Digital Exchange (settlement). - Project Jura (cross-border CBDCs).

Platform	Type	Key Features	Compliance and control mechanisms	Applications
Hybrid (e.g. Quorum)	Hybrid	• Different technical solutions combining public and private features. • Used for trading activities on private networks, or for settlement on public blockchains.	• Varies by implementation. • Can include privacy enhancements, regulatory controls, and interoperability.	• Project Ubin (Singapore). • Tokenised gold bars. • Interoperability initiatives (Hyperledger Cacti).

Source: Author's elaboration.

As the leading public blockchain for token issuance, Ethereum serves as the main force behind the tokenisation process. The platform enables the creation of smart contracts, which allow anyone to establish and manage tokens that can represent nearly any type of asset. The Ethereum Request for Comment (ERCs) standards outline the interface specifications for tokens that operate through smart contracts on Ethereum. The Ethereum network developed both standards, a fungible token (i.e. the ERC-20) and a non-fungible token (NFTs) (i.e. the ERC-721) enabling operations seamlessly across different wallets and exchanges, according to Vogelsteller and Buterin (2015) and Entriken et al. (2018). The emergence of tokenised assets created a thriving environment for stablecoins, potentially CBDCs and other digital representations of commodities and securities. Several stablecoins like the USDC (S&P Global, 2024a), and the PAX Gold token, function as ERC-20 tokens, maintaining full backing through external reserves of dollars or gold (Paxos, 2024). Investment companies have released on Ethereum, security tokens, representing tokenised shares and bonds that trade through alternative trading systems, by making use of regulatory exemptions.

The permissionless public structure of Ethereum enables users from any location, to exchange tokens under smart contract conditions, which allows wide market access. Scalability challenges and fee structures present significant obstacles for Ethereum, as network congestion leads to high transaction fees and limited throughput, which impacts high-volume financial markets. Continuous upgrades to Ethereum such as Layer-2 and Proof of Stake scaling networks are intended to resolve main issues (Ethereum Foundation, 2025). However, privacy remain a concern for confidential transactions. The public visibility of trades presents difficulties for financial institutions, who manage sensitive data. The combination of Ethereum's early market entry and its expansive developer ecosystem positions it as a primary platform for asset tokenisation in decentralised finance. The primary ERC standards that apply to asset tokenisation consist of a series of specific tokens, each with its own peculiarities. First proposed in 2015, and rapidly gaining popularity by 2017, the ERC-20 established a

standardised interface for fungible tokens. Fungible tokens serve as exchangeable elements, since every token shares the same type and value with its counterparts. The ERC-20 standard includes basic functions such as *totalSupply*, which shows total token supply, and *balanceOf*, which shows token balance for an address, along with *transfer* and *transferFrom* functions, to move tokens, and an *approve/allowance* system, that lets third parties spend tokens on behalf of someone (Vogelsteller and Buterin, 2015). The basic yet universal features of ERC-20 made it the preferred choice for the Initial Coin Offerings that occurred during 2017-2018.

The process of tokenising assets like gold, through platforms such as PAX Gold, or real-estate SPVs, usually make use of the ERC-20 standard, compatible with Ethereum wallets. ERC-20 tokens lack built-in restrictions, complex logic functions, and operate similarly to digital bearer instruments. The ERC-721 became a standard for tokens non-fungible in early 2018, as it established a system for tokens which could not be exchanged uniquely with other tokens, according to Entriken et al. (2018). The ERC-721 token system assigns every token an exclusive identifier, called *tokenId*, while designating a specified owner. The rise of the standard began with CryptoKitties, collectible digital cats, followed by an expansion into the wider NFT art and collectibles market. The ERC-721 serves as the standard for representing unique items or contracts, when asset tokenisation takes place.

The ERC-1155 is a versatile standard that can support the management of multiple token types, through one smart contract. ERC-1155 contracts rely on *tokenId*, which can represent a fungible token quantity (like ERC-20 tokens) or multiple distinct tokens (like ERC-721 non-fungible tokens). This standard is popular in gaming (for example, one contract can manage a game's whole inventory of items, where the contract under one roof contains fungible commodities' coins such as gas, cars, elements that may be fungible if they are identical; and unique attributes for the drivers, which are non-fungible. ERC-1155 serves as a practical solution for issuers who need to manage various token series, such as multiple bond types or commodity tokens, through one unified contract to maximise efficiency. While ERC-721 and ERC-20 receive more attention in financial applications, ERC-1155 serves as a hybrid option, between fungible tokens and non-fungible tokens. Polymath and other developers launched in 2018 multiple security-token standards for Ethereum, through dedicated proposals (Polymath, 2018).

Developers created standards to integrate regulatory controls into tokens, such as the ERC-1400, and related tokens like ERC-1410 and ERC-1594 (Ibáñez, Hoffman and Choudry, 2024). Security tokens with partitions, enable token to create tranches, differentiating between

restricted and unrestricted shares, and introducing built-in transfer controls, e.g. pre-transfer validation functions, to enforce allow-list permissions or lock-up periods.

The ERC-1594 standard enhances the ERC-20 functionality by introducing a *canTransfer* feature, which checks potential transfer success, to ensure regulatory compliance is maintained (Dossa et al., 2018). The ERC-1410 enables partitioned balances to separate shares that fall under different registration requirements, like the USA Regulations S for non-US investors and the USA Regulations D for USA accredited investors, until they can be combined. The ERC-1400 standard did not achieve universal adoption like the ERC-20, mostly due to its complexity and the creation of project-specific variants but they nonetheless had a significant impact on security-token platforms' design. Examples are the tokens developed by Polymath through its security-token-issuance platform, which extended the ERC-20 standard, with modular restrictor plugins, to control token ownership and to ensure trading permissions (Polymath, 2018).

A new standard is called the ERC-3643 or the Token for Regulated EXchanges (T-REX) standard, which became official in late 2023 (Tokeny, 2023a). Tokeny developed this standard which extends the ERC-1400 concepts, to establish an extensive framework for securities' tokenisation. ERC-3643 establishes an identity protocol called ONCHAINID, which ensures all token holders maintain verified identities, while the token transfers perform compliance rules' verification (Lebrun et al., 2021). Multiple modules within the contract, manage compliance and sanctions screening, alongside child contracts, and create a powerful and complex standard, suited for enterprise applications. The Ethereum community recognised the ERC-3643 as a standard in December 2023, which established its acceptance as a security-token standard. The ERC-3643 integrates regulatory compliance measures such as KYC/AML and transfer the controls directly into the token protocol, instead of using additional off-chain processes. The ERC-3643 token conducts automatic verification to ensure the counterpart A is a valid investor, who meets all necessary criteria, before accepting a security token from counterpart B (Tokeny, 2023b). Real-world asset tokens require these measures, as regulatory standards mandate the enforcement of screening rules.

The Ethereum ecosystem includes ERC-20 tokens for basic fungible assets such as currencies and funds, the ERC-721 tokens for distinctive items like art NFTs and unique real estate titles, alongside newer standards like the ERC-3643 for regulatory compliance in securities. These distinctions primarily involve whether assets are fungible or unique, as well as, whether the transfer system is open or controlled. An ERC-20 gold token provides no built-in functionality for redemption rights, or custody proof, which requires off-chain management;

while an ERC-3643 security token enforces contract-level authorisation, while confirming user identity certification.

The Stellar protocol operates as a public blockchain for digital assets and payments, which supports built-in token creation capabilities and delivers fast and low-cost transactions, according to Mazieres (2016). The Stellar protocol enables basic asset issuance without smart contracts, by allowing any account to create a token with a code of up to twelve characters and a public key of the issuing account, as identifier. Once the trust relationship is established, by creating a trustline, others can possess that asset. This mechanism ensures the standard token properties within Stellar, as every asset has amount, issuer, and code attributes. The platform uses a native decentralised exchange (DEX) and trustlines model. The built-in decentralised exchange and the Stellar wallets manage assets in a standardised manner, according to Lokhava et al. (2019). Users may open a trustline to an asset code, which demonstrates their explicit trust in the issuer holding the underlying assets. The platform enables easy token issuance that bypasses the need for custom smart contract development. Users can enable compliance features, by configuring account flags, e.g. for transfer approval for each token, or for permitting holder screening.

The Stellar Consensus Protocol achieves transaction confirmation in seconds, without using mining, which makes it ideal for high-throughput applications, such as retail payments or micro-investments (Mazieres, 2016). Stellar assets can be flagged with issuer-enforced restrictions: the *RequireAuthorisation* flag allows issuers to mandate approval for every account that wants to hold their token, through authorisation or de-authorisation of trustlines. The ability to enforce authorisation requirements allows issuers of regulated assets, to both verify KYC status among token holders and to revoke access, to freeze assets on non-compliant accounts. The system incorporates the *Immutable* settings and the *Clawback* feature, which lets issuers retrieve their tokens on specified conditions, including regulatory requirements or operational errors (Lokhava et al., 2019). The compliance requirements can be met effectively through these features, without additional custom coding. Stablecoin issuers may have the authority to freeze stolen assets and reclaim tokens, in case of mistakes. Its unified model means that Stellar operates under one core protocol, rather than having distinct standards (like the Ethereum ERC-20 or ERC-1400).

The Stellar network (Stellar Ecosystem Proposal - SEP) presents guides, which establish interaction protocols, between off-chain and on-chain processes for specific asset applications. The SEP-6 and the SEP-24 guidelines establish methods for performing compliant fiat token deposits and withdrawals, through anchors. The SEP-8 establishes that

regulated assets require an approval step, which ensures that network execution of transactions happens only after off-chain server approval, allowing detailed controls, including issuer review of transfers above specific limits. Other standards are also available such as: SEP-41 (Stellar Asset Contract Interface); SEP-56 (Tokenised Vault Standard); SEP-50 (NFT); ERC-3643 (Stellar Development Foundation, 2025). The implementation of SEPs enables issuers of security tokens to maintain regulatory oversight, while using Stellar's network capabilities. An example of Stellar tokenisation is provided by Circle, which issues its USD Coin (USDC) token, on both Ethereum and Stellar networks, to benefit from Stellar's lower transaction costs for payment applications (S&P Global, 2024a). The IBM World Wire's settlement network demonstrates regulated institutions' trust in Stellar's built-in asset features, by tokenising multiple banks' fiat currencies for cross-border transfers (IBM, 2020a). Through the Stellar network, Franklin Templeton recorded their tokenised money market fund shares, which reached millions of USD in asset management during 2023, showing institutional confidence (Franklin Templeton, 2024). Despite its utility, Stellar supports only fundamental smart contract scripting, this a limitation when compared to Ethereum's capabilities. Stellar offers efficient tokenisation solutions for currencies and basic securities with established issuers, while maintaining compliance with regulatory standards.

The Tezos public blockchain selected the Proof-of-Stake, as consensus mechanism. The system has on-chain governance, enabling protocol improvements, and does not require hard forks. It represents a platform capable to attract institutional users who seek stability (Goodman, 2014). Smart contracts, written in either Michelson or higher-level syntaxes (such as LIGO and SmartPy), which developers can formally verify, are adopted in Tezos, to ensure their safety for critical financial applications (Webisoft, 2025). On the Tezos platform, developers have established token standards comparable to Ethereum. Tezos features two token standards, with FA1.2 functioning as an early fungible token standard, while FA2 serves as a unified standard, which manages multi-asset tokens under one system. The FA1.2 standard (TZIP-7) represents Tezos' implementation of the ERC-20 token standard. The FA1.2 standard identifies entry points that act as public methods for transferring and approving fungible tokens, within Tezos smart contracts. Initial Tezos-token projects utilised the FA1.2 standard, for example the tzBTC that represents a token backed by Bitcoin (tzBTC, 2020).

The FA2 (TZIP-12) standard was introduced in 2020, it provides multi-asset functionality in Tezos, through one unified interface and it supports both fungible assets and non-fungible assets (Mishura and Mondet, 2020), which follows a similar concept of the ERC-1155 standard. The FA2 token identification system assigns IDs to tokens, where each ID can represent either one or multiple units. The standard provides operator functionalities, in line

with the ERC-1155, allowing users to assign operators for their token management. Tezos implemented an adaptable standard that could support the distinct types of NFTs and both fungible and game assets, appearing on the platform. The FA2 standard can enforce restrictions through custom contract logic, and it has become the default choice for many Tezos-based marketplaces and projects, including art NFTs and game tokens (Mishura and Mondet, 2020). Tezos uses on-chain governance to enable platform evolution, when token standards require modifications. Tezos enables the conversion of real estate and fine art items, into digital tokens for real-world application. The commitment of Tezos to compliance and formal governance processes has drawn attention for institutional pilot projects; however, Tezos capabilities are limited when compared to Ethereum, due to fewer exchanges and custodians, thereby restricting liquidity. Other tokenisation projects have been performed on public blockchains such as Polygon, Avalanche, Binance Smart Chain (BSC).

Financial institutions have investigated permissioned (private) ledgers, alongside public chains to enable asset tokenisation, within networks containing recognised participants. In 2019, Forge, a digital-assets division of Société Générale, used the Tezos blockchain to issue a EUR100 million covered-bond, as a security token (Société Générale, 2020). Banque de France worked together with Société Générale, to assess a digital-euro CBDC for settlement purposes, through a repo transaction (Société Générale, 2024). Private and consortium blockchain platforms follow strict regulatory requirements for traditional market infrastructures, by focusing on their privacy, governance, and performance standards (Catalini and Gans, 2016). Asset tokenisation projects are being undertaken using blockchain platforms such as Hyperledger Fabric and R3 Corda, or Quorum and DAML-based systems, developed by Digital Asset. Private blockchains such as Fabric and Corda prioritise privacy and governance features, which make them appropriate for institutional-level tokenisation initiatives.

The Linux Foundation's project supports Hyperledger Fabric, as its open source blockchain platform. Unlike public blockchains, Fabric is permissioned. In Fabric's blockchain system, only validated participants can join the network (Androulaki et al., 2018). Fabric uses a modular architecture that uses Chaincode for smart contracts, while enabling customisable consensus mechanisms for network requirements. The platform avoids the use of a native cryptocurrency, which makes it attractive to businesses looking to avoid unstable tokens and mining operations (Androulaki et al., 2018). Through its Chaincode feature, Fabric enables asset tokenisation by creating asset records, which become ledger entries.

The Token Software Development Kit (SDK) establishes a standard for token management protocols on Fabric, by setting rules for issuing, moving, and eliminating tokens (Hyperledger

Foundation, 2022). Both fungible and non-fungible tokens can be deployed on Fabric, while maintaining transaction privacy between participants, by using its channel architecture and confidential data collections. The we.trade platform serves as a practical example of Fabric's capabilities, through its management of trade finance obligations and invoices with tokenised assets. The World Wire project by IBM, combined Stellar technology for token issuance with Hyperledger Fabric technology, to manage private institution transactions (IBM, 2020a). A bank consortium might use Fabric to tokenise syndicated loans. The loan-token transfers may be visible only to the banks involved and regulators participating in the channel, which keeps the process confidential. Fabric proves its worth through its ability to process large transaction volumes within private networks, and for its compatibility with enterprise-identity systems that support KYC/AML requirements. The main advantages of Fabric include high transaction throughput, combined with privacy features and compatibility with enterprise identity systems, to support KYC/AML requirements. The main disadvantage of this system is the limited liquidity and network effects it experiences, in comparison to public chains. The Hyperledger Cacti represents an initiative that seeks to create interoperability across multiple Fabric networks, and between Fabric and other public blockchain networks (Hyperledger Foundation, 2023).

The R3 Corda platform functions as a widely adopted DLT, primarily targeting financial sector applications. Corda operates differently from standard blockchains, as it limits data access, by sharing information exclusively with necessary transaction participants (Brown, 2019). The design of Corda enables the creation of legal agreements, which ensures strong alignment with financial contracts. R3 developed a token Software Development Kit (SDK) for Corda which enables the tokenisation of assets through templates, representing these assets as ledger states. Corda differentiates between fungible and non-fungible token states, using an approach comparable to cryptocurrencies. The token SDK on Corda distinguishes between fungible token states, which represent divisible assets, such as currencies or commodities, and non-fungible token states, which represent unique assets or identifiers. The Token SDK establishes participant roles, including issuers, owners, and observers.

The HQLAx platform represents a major consortium of banks that uses Corda, to create digital tokens for high-quality liquid assets such as bond baskets, to execute immediate collateral exchanges (HQLAx, 2024). HQLAx uses tokens known as Digital Collateral Records, to represent external securities ownership, which facilitates immediate swaps on Corda for faster repo and securities lending collateral movement (HQLAx, 2024). Since its launch in 2019, Corda has shown its effectiveness in regulated environments. The SIX Digital Exchange in Switzerland implemented Corda for its settlement functions, however it deployed its own DLT

stack, while maintaining service interoperability and technical connectivity with Corda (SDX, 2021a). Corda provides privacy advantages, through direct interactions between parties, along with the capability to link token transfers to legal contracts, as every transaction can be connected to legal documentation. The governance structure of Corda networks usually involves consortium operation, which includes multiple banks with a governing body, to ensure compliance and recourse mechanisms. Corda restricts its user base to institutional or accredited investors, as its network operates on known and permissioned nodes, which excludes broad public involvement. Corda's achievements in interbank trading and central bank projects, including Project Jura (which evaluated cross-border CBDCs with tokenised assets), demonstrate that permissioned DLT systems can successfully operate tokenised financial products, within current legal boundaries as shown by the BDF, BIS, and SNB (2021).

The financial industry is seeing the development of hybrid systems that use permissioned networks for trading activities, while relying on public blockchains for settlement processes. Other private/consortium DLTs include the Quorum created by JP Morgan, which is a private Ethereum fork, designed to enhance privacy and which enabled gold bars to be tokenised, along with other initiatives, such as Project Ubin in Singapore, according to MAS (2025b). The summary of the standards for asset tokenisation is available in the next table.

TABLE 13: STANDARDS FOR ASSET TOKENISATION

Standard	Platform	Type	Key Features	Compliance & Control Mechanisms	Applications
ERC-20	Ethereum	Fungible	- Standard interface for fungible tokens. - Basic functions: <i>transfer</i>, <i>approve</i>, <i>balanceOf</i>. - Implemented for Initial Coin Offerings, stablecoins and tokenised assets.	- No embedded limitations. - Compliance ensured through off-chain processed or smart contracts.	PAX Gold, real estate SPVs.
ERC-721	Ethereum	Non-fungible	- Unique identifier (<i>tokenId</i>) - Standard implemented for collectibles, NFTs, unique assets. - Each token is distinct.	- No built-in compliance. - Uniqueness enforced by protocol.	NFT art and CryptoKitties.
ERC-1155	Ethereum	Hybrid	- Multi-asset support available in one contract. - Supports both fungible and non-fungible tokens.	- Operator permissions. - Flexible management. - Custom logic possible.	Gaming assets, multiple bond/commodity tokens.
ERC-1400/1410/ 1594	Ethereum	Security	- Security tokens with regulatory controls. - Partitions, transfer restrictions, tranches. - Pre-transfer validation functions.	- Built-in compliance. - Allow-lists, tranches, pre-transfer checks.	Polymath, Securitize.
ERC-3643 (T-REX)	Ethereum	Security	- Security tokens with <i>ONCHAINID</i> identity protocol. - Compliance at protocol level.	- Automatic process for KYC/AML and sanctions screening. - Transfer controls. - Compliance modules.	Enterprise securities, regulated assets.

Standard	Platform	Type	Key Features	Compliance & Control Mechanisms	Applications
Stellar Ecosystem Proposal (SEPs)	Stellar	Fungible	• SEP-41 (Stellar Asset Contract Interface); SEP-56 (Tokenised Vault Standard); SEP-50 (NFT); ERC-3643. • Low transaction cost. • Built-in token creation. • Trustlines and DEX. • Transaction confirmation in seconds, without using mining, for high-throughput application • Compliance flags (Require Authorisation, Clawback). • Supports only fundamental smart contract scripting, for basic features.	• Require Authorisation for KYC. • Clawback for asset recovery in case of regulatory requirements or operational errors.	• IBM World Wire, Franklin Templeton. • Circle USDC on both Ethereum and Stellar.
FA1.2 (TZIP-7)	Tezos	Fungible	• PoS as consensus mechanism. • Similar to ERC-20. • Used for early Tezos tokens.	• Entry points for transfer/approval. • Custom contract logic.	• tzBTC, early Tezos tokens.
FA2 (TZIP-12)	Tezos	Multi-asset	• Unified standard for fungible and non-fungible tokens. • Fewer exchanges and lower liquidity vs Ethereum. • Operator permissions. • Multi-asset management.	• Similar to ERC-1155. • Custom contract logic for restrictions. • Operator permissions.	• Default for Tezos NFTs/ games.

Source: Author's elaboration.

4.1.3. LIFECYCLE MANAGEMENT PROCESSES

The tokenisation of assets extends beyond its software code, to encompass the full journey from the token creation to its retirement, and it is linked to the lifecycle of the underlying asset. The lifecycle management includes minting and issuing tokens, along with linkage of the underlying assets, through custody or legal agreements, and the automated smart contract features that may be implemented for rule enforcement, distribution, trading and settlement mechanisms, that manage token transfers, and the eventual redemption or burning processes. The operational processes vary depending on different asset types and platforms. The minting refers to the process of producing new tokens for the first time on the blockchain.

- In Ethereum-like chains, the minting process, the issuer sets up a token smart contract or employs a factory contract, which includes a function for generating new tokens, usually known as minting. During the tokenisation of a new asset, the issuer technically calls the *mint(investor_address, amount)* function on their token contract, to distribute tokens to an investor. Once the investor performs a fiat payment off-chain and completes KYC verification in a Security Token Offering (STO) process, the issuer uses a platform to mint the corresponding security tokens into the investor's wallet. At contract deployment, the token contract may create the entire supply, which gets assigned to the issuer for subsequent distribution. The Non-Fungible Token (NFT) minting process requires the generation of a new token ID that includes metadata, to define the distinct asset.
- In Stellar, the minting process involves issuing assets directly from the issuer account. The issuer account can transfer a few units of a newly created asset, identified by a specific code, directly to the investor's Stellar account address. Sending assets from an issuer account creates new units, which serves as minting, as the issuer can generate these units up to defined limits or until their issuing power ends (Stellar Development Foundation, 2024).
- The minting process in Fabric or Corda platforms typically involves the initiation of a transaction that generates a new token state. An issuer node on Corda creates a new *TokenState* on the ledger, through an *IssueToken* flow, which defines the token type and quantity, along with the recipient, while marking it as issued, by the issuer with proper signatures. The Fabric ledger allows the addition of new entries or balance increments, through authorised Chaincode function calls, which require endorsements from necessary peers. The minting of token types requires designated issuer roles, which must be enforced either through chaincode logic or network governance (Hyperledger Foundation, 2025).

The process of creating new tokens needs to maintain a direct linkage with their corresponding underlying assets. The tokenisation process demands either asset locking or asset representation mechanisms, to prevent its simultaneous use both off-chain and on-chain, which would constitute double-spending. Multiple options are possible to ensure this linkage. For instance, the process of minting PAX Gold tokens by Paxos, involves creating a separate gold bullion asset stored in a vault, for each token produced, and it validates this direct backing with audits and real-time attestations (Paxos, 2024). A legal Special Purpose Vehicle (SPV) or a Trust structure may allow a legal entity to possess real estate property, while issuing membership or profit-sharing tokens, with a subscription agreement that connects each token to specific legal rights, held by the SPV. In tokenising Bitcoins, Wrapped Bitcoin locks BTC in custody and mints corresponding ERC-20 tokens, named WBTC (tzBTC, 2020), in an analogous manner, a custodian could lock listed shares and issue tokens for the corresponding amount. To unlock the underlying assets, users must burn the corresponding tokens, to free the secured underlying assets.

Native digital assets are directly created in a way that digital securities exist only as blockchain tokens. An example is represented by the Ethereum bond tokens issued by the EIB, which serve as the official bond record (EIB, 2021). A custody process is expected for physical and financial assets, which are not natively digital. When dealing with gold or fiat money assets, a custodian holds the asset and ensures that each token created corresponds to an unencumbered physical asset in their custody. To continue with the previous example, Paxos allocates one ounce of gold from its vault to the token holder, in case of minting of a PAXG token (Paxos, 2024). The redemption process of a token, also known as burning, result in the release of either the physical or its cash equivalent, which subsequently decreases the amount held in custody. Through routine audits and instant attestation systems, administrators ensure that circulating tokens match reserve assets listed. A one-to-one backing model operates as the essential mechanism behind the functionalities of tokens, the physical and the tokenised assets.

A direct custody function cannot always be used for assets like real estate and equities. To cater for these scenarios, a legal entity may assume the ownership of the real asset. The token represents a share of ownership or beneficial interest within the associated entity. A legal entity may hold property rights to a building and distribute membership tokens, through an STO. The legal connection can be represented by a subscription agreement, which declares that the ownership of a token provides entitlement to one share of the legal entity, along with its economic rights. The blockchain functions as the ledger for recording asset ownership. Legal documents must reference the token using its contract address (or *tokenID*), to link the digital

record to the physical ownership. In fact, the blockchain ownership ledger requires legal documents to refer to the token (by means of contract address or *tokenID*), to establish the connection between the digital record and the real-world claim. Legal frameworks such as the Switzerland's ledger-based securities law, establish token entries as direct ownership proof, thus creating a strong linkage (Swiss Federal Council, 2021). In these cases, the token functions as proof, but does not function as the primary security instrument, which remains stored in a conventional registry.

When an asset exists digitally, before the tokenisation process, there is a requirement to lock the asset to create its token representation. Wrapped cryptocurrencies serve as a prime example, for instance wrapping Bitcoin on Ethereum consists of securing a BTC in a custody wallet, and generating ERC-20 tokens, named WBTC (Bitstamp, 2024). The process of tokenising securities requires a custodian to lock the physical shares in a segregated account, before generating a token that mirrors the share on a direct basis. This system prevents the underlying asset from being transferred or double-spent, until the corresponding token has been redeemed. There are cases, where the token functions as the asset itself, without any external asset counterpart. Native digital bonds and shares exist as tokens, without traditional certificates, since those tokens represent the assets. The EIB's Ethereum bond tokens serve as the definitive record of the bond, and no physical paper certificates exist (EIB, 2022). When native digital assets are created through minting, this process represent directly their issuance. Legal confirmation of the tokens as a security is necessary, which can be accomplished through the selection of a legal framework that permits this classification such as the Luxembourg regulatory framework, for the EIB's Ethereum bond (EIB, 2022).

After minting, tokens become property of either the initial investor or the issuing entity. Investors must provide payments, when the issuer distributes the assets. In case of an STO, the activities can be automated. A sale contract on Ethereum collects Ethereum cryptocurrency (ETH) from senders, before generating matching asset tokens. The sale and minting processes for security tokens often use semi-automated platforms, like Tokeny, which deliver tokens only after authorising investor addresses (Tokeny, 2023a). The minting phase sets the supply, tokens may come with a fixed supply that cannot be changed, alternatively the supply can be dynamically adjusted, by minting new tokens or burning existing ones, based on asset transfers. In these instances, a tokenised open-end fund creates new tokens, when investors add money, and it redeems tokens, when investors withdraw their money.

The design of many tokens includes the ability to exchange them for their corresponding underlying asset. For example, stablecoins usually allow redemption for fiat money (S&P

Global, 2024a). A token holder may return the token to the issuer, in exchange for fiat currency, based on established terms. Commodity tokens allow users to exchange them for physical commodities, but redemption usually requires substantial quantities, due to practicalities. The token contract incorporates a burn function, which enables the destruction of tokens, through activation by the issuer or an authorised entity, upon receiving the underlying asset. In this scenario, investors deliver the token to the issuer's address and requests redemption through a function call (or off-chain process), which leads to the issuer validating the request prior to transferring fiat or physical assets off-chain, before proceeding to eliminate the redeemed tokens from circulation, through a burn function call. This process ensures that the circulating token supply corresponds to the assets held by the issuer (Gregory and Mini, 2025). Security tokens remain non-redeemable until a specified liquidation event occurs, such as the sale of the asset, in the case of a real estate token. The token remains active throughout the asset lifespan, until the issuer disburses proceeds to token holders, before burning all tokens (Gregory and Mini, 2025).

The distinct features of each tokenised asset are programmed directly into the token. Fungible tokens usually allow division to a specified decimal point. This divisibility allows fractional ownership. A real-estate token could be split into units, which represent a percentage of the property. A non-fungible token ERC-721 remain whole and indivisible, but fractional NFTs can be created by using ERC-20 tokens, to represent shares in an ERC-721 asset, thereby enabling multiple owners to hold parts of an NFT (Entriken et al., 2018). A single token might stand in, for any member of a specific asset class. A token can represent a barrel of crude oil, remaining interchangeable with any other token for the same grade of crude oil barrels. A token might be connected to an individual lot, which results in uniqueness. The choice of the token design affects the liquidity, in fact fungible tokens are more prone to trading, but provide limited detail on specific item attributes (Vestr, 2025). Token contracts possess the ability to manage token splits, in a process equivalent to stock splits, through balance and denomination adjustments. A smart contract may automatically create extra tokens for holders, when a company doubles its shares proportionally, or alternatively deploys a new token and make swaps, which requires manual execution. Advanced systems may enable token holders to vote on proposals, using on-chain voting logic, with mechanisms like ERC-20 snapshots or integrated functions (Vogelsteller and Buterin, 2015).

Tokens designed for regulated assets, such as the ERC-3643, create a connection between each address and its corresponding identity, which is maintained off chain through specific mechanisms, like registry contracts. During a transfer operation, the contract verifies that both senders' and receivers' addresses are part of the approved registry, and it confirms that the

transfer abides by regulations, tied to their investor classes. The established linkage prevents tokens from being held by individuals, who lack legal authorisation to possess them, despite the circulation of tokens in platforms. The ERC-3643 facilitates reporting and compliance, by providing issuers with information on token holders, as opposed to dealing with anonymous addresses, which securities regulations typically prohibit, due to the shareholder-of-record requirements (Lebrun et al., 2021). The process of preserving the link between assets and their corresponding tokens requires continuous management. Audits of custodians are routinely performed, and smart contracts are also subject to auditing processes, to ensure code accuracy.

Tokens may become fractionally reserved, when minting is done improperly. This happens when someone fraudulently creates tokens without proper backing. Regulatory frameworks mandate that token issuers follow similar disclosure and audit procedures, as traditional security issuers (Park, Lee and Kim, 2024). Events impacting the value of the underlying asset represent a critical component of the lifecycle management of tokenised assets. When assets suffer damage or depreciation, this impacts the associated token, as its value will decrease, however the communication of this change remains unclear. In financial markets, the trading price incorporates the information about the state of the assets. For instance, if a bond defaults or receives partial repayment, the linked token shall adjust its redemption value or cash-flow projections. Several platforms address this issue using trusted data feeds, also called oracles, or governance measures to modify token parameters. A tokenised bond may use an oracle to provide interest rate information or default status, which activates a smart contract to enter a specific state and possibly halt transactions until restructuring occurs (Fekih et al., 2023).

Smart contracts can embed rules across tokens, which automate and enforce operations that would usually need intermediary intervention. Financial assets often require restrictions on transfers, for example to enable transactions solely between approved addresses, or to enforce transfer lock-up periods. Ethereum tokens can enforce transfer conditions, by overriding their transfer function, as demonstrated by ERC-1400 (Polymath, 2018) or ERC-3643 tokens (Lebrun et al., 2021). During its first year after launch, a startup's equity token could be completely non-transferable, to meet lock-up agreement requirements. The contract might automatically remove the restriction after one year, or require manual intervention, to change a specific flag to alter the restriction. Automated restrictions enable compliance verification, without the requirement to manually review off-chain agreements.

Another potential use case is related to the payment of cash flows, from the tokenised assets directly to the token holders. A smart contract can receive dividends in the form of stablecoin

or CBDC for tokenised equity, and then distribute payments proportionally to all token holders, based on their share at the record date. Early tokenised bond pilots showed how token holders received interest payments through on-chain transactions, based on their token ownership on the payment date (Cisar et al., 2025). The MakerDAO's DSR contract enables token holders to earn automated interest payments in DAI stablecoin, whenever they lock their DAI tokens, functioning similarly to bonds that pay interest without manual intervention (MakerDAO, 2025). Structured finance uses waterfall distributions, which establish intricate payment rules that prioritise and sequence financial payments among different parties (like the payment structure of mortgage-backed security tranches). The rules that guide payment distribution can be encoded into smart contracts, which automatically execute when a payment arrives. When borrowers remit their mortgage payments, the smart contract disburses funds starting with senior tranche tokens, before allocating money to mezzanine tranches. In this way, structured products can experience a significant decrease in administrative overhead, while maintaining transparency. Smart contracts can facilitate atomic transactions that execute only when specific conditions are met.

An atomic swap system eliminates counterparty risk because it enables transactions to occur instantly without a central clearinghouse, through a simultaneous exchange process. A delivery vs payment transaction can be structured so that the security token of counterpart one transfers to counterpart two, and counterpart two's cash token transfer to counterpart one, may occur together or may not execute. Platforms have different mechanism for the execution of atomic transactions. The Ethereum blockchain allows atomic swaps through HTLCs (Hash-Time-Locked Contracts) or by executing successful transfers, through a transaction that interacts with both token contracts. Corda ensures multi-legged transactions, that either succeed or fail simultaneously. The achievement of peer-to-peer trade with immediate settlement represents the objective of settlement systems, commonly known as atomic Delivery-versus-Payment (DvP) (Vestr, 2025). Another conditional transfer example is escrow or programmable escrow, with tokens stored in a contract, which releases them to the buyer after the payment from the buyer is confirmed, acting as an operational programmable escrow agent. Smart contracts can administer certain operations for assets such as loans or leases without manual intervention.

Tokens function as dynamic instruments that react to external events beyond their static representation. A smart contract for a tokenised loan would automatically withdraw a payment from the borrower's digital wallet, whenever a payment deadline is met, or can mark the token as overdue and begin collateral transfer, in case the payment is missed. In the supply chain finance tokenisation process, a token representing an invoice may automatically cancel, upon

direct payment of the invoice, alternatively it can create a penalty token, when payments are delayed. Automated features can support Internet of Things (IoT) systems, with external information agents that could enable actions such as automatic insurance payouts, in case flights are confirmed as delayed or cancelled, by third-party air control systems.

Smart contracts can also automate compliance monitoring, ensuring compliance with investor ownership limits, by blocking any transfers that would result in an investor exceeding a specified percentage of total shares. Tokens can be programmed to prevent transfers until a future date, by implementing holding periods, through timestamps. The provision of information from the ledger to regulators or authorised parties in permissioned frameworks enables automated compliance reporting, such as tracking current token holders in ERC-3643 tokens (Lebrun et al., 2021). A summary of the design choices and attention points for the tokenisation of the assets is available in the next table.

TABLE 14: DESIGN CHOICES, SOLUTIONS AND ATTENTION POINTS FOR ASSET TOKENISATION

Area	Design choices	Solutions adopted	Attention points
Asset model	- Natively digital, with assets issued directly on-chain. - Wrapped or proxy assets which are off-chain records.	- ERC-3643. - ERC-1400/1410.	- Ensure asset linkage 1:1. - Determine need for legal dematerialisation.
Ledger	- Permissioned platforms (SDX, Quorum) - Permissionless platforms (Ethereum, Polygon).	Consensus: Proof of Authority; Byzantine Fault Tolerance; Smart-contract Virtual Machines.	Throughput and privacy trade-offs.
Settlement model	- Atomic Delivery-versus-Payment (DvP). - Atomic Payment-versus-Payment (PvP).	- DL3S Solution (BdF,2023). - TIPS Hashlink (Bdl, 2022). - Trigger solutions (Deutsche Bundesbank, 2024). - Project Helvetia (BIS, SNB and SDX, 2022).	Reduce settlement cycle from T+2 to near-real-time.

Area	Design choices	Solutions adopted	Attention points
Interoperability	• Single-ledger versus multi-ledger routing. • Cross-chain bridges.	• MAS-GL1 design principles (MAS, 2024).	• Confirm network effects and systemic risk.
Lifecycle management	• Corporate actions, coupons, voting embedded in smart contracts.	• Oracles (Chainlink), ISO 20022 messaging bridges.	• Automation lowers back-office cost but raises oracle risks.

Source: Author's elaboration.

4.1.4. TRADING AND SETTLEMENT

After issuance, tokens become tradable among users until settlement either through payment exchange or redemption for the asset they represent. Tokens can be traded on secondary markets, including decentralised transfers (i.e. through regulated digital-asset exchanges, or over-the-counter trades through direct wallet transfers). Traditional equity or bond markets separate execution and settlement into distinct processes, where execution takes place on an exchange followed by T+2 days delivery, through clearing houses (WEF, 2025). The settlement process for token trades is markedly different from traditional finance, as on blockchain platforms, it is simultaneous to the transfer of the token. During trades, when a token is transferred from counterpart one to counterpart two, the counterpart two perform the payment through cryptocurrency, stablecoins, tokenised deposits or CBDC to counterpart one. The transaction becomes final within minutes after inclusion in a blockchain block, ensuring technical settlement finality. Atomic DvP represents a significant advancement in tokenisation, as it connects asset token delivery, with payment delivery to ensure both transactions occur at once or they do not occur at all (Lee, Martin and Müller, 2022). The settlement of one transaction element depends entirely on the settlement of the other transaction element. Programmatic atomic DvP at a global scale, could potentially become achievable through DLT, as financial institutions rely on centralised clearing systems, to maintain asset delivery and payment synchronisation.

A smart contract or coordinated transaction can make sure that a tokenised bond moves from counterpart one to counterpart two at the same time when cryptocurrency, stablecoins, tokenised deposit or CBDC move from counterpart two to counterpart one, thereby removing settlement risk, e.g. eliminating the Herstatt risks (ECB, 2007), without requiring a third-party

central counterparty (Lee, Martin and Müller, 2022). This has been demonstrated through pilot projects, e.g. during EIB's Ethereum-based digital bond issuance, the bond token delivery and the CBDC token in euro from Banque de France were executed in a synchronised manner (EIB, 2021). The programmability feature of smart contracts enables atomic settlement to handle multiparty transactions, and intricate trade arrangements such as basket swaps and chained trades. The implementation of atomic settlement decreases counterparty risk, while accelerating transaction settlement times to immediate execution, instead of a typical T+2 days' timeframe (Lee, Martin and Müller, 2022). Atomic DvP helps to decrease the time assets and cash remain unsettled, which leads to reduced collateral or capital requirements throughout the settlement procedure (Vestr, 2025), thus decreasing systemic risks.

Token trading and settlement operations may occur through different mechanisms. In Peer-to-Peer (P2P) transfers, two parties first settle on a price off-chain and then conduct a token exchange on-chain (Hays et al., 2021). Two parties may reach an agreement which involves counterpart one selling tokens to counterpart two. After receiving cryptocurrency, stablecoins, tokenised deposits or CDBC, from counterpart two at a specified address, counterpart one transfers the token to counterpart two's address. The transaction process involves two distinct steps requiring trust or sequential risk, because counterpart two sends payment first, expecting counterpart one to follow through with sending the tokens. The risk of sequential transactions can be reduced by conducting the exchange through an atomic swap or by engaging an escrow agent or Decentralised Exchanges (DEXs) (Kivilo et al., 2025). Tokens that reside on public blockchains can be traded through Decentralised Exchange protocols. The DEX protocols such as Uniswap provide a trading platform for tokens, when they are on public chains with DeFi infrastructure (Hays et al., 2021). Numerous tokenised real-world assets face restrictions, which prevent their aggregation in an open decentralised exchange. DEX platforms integrate automated market-making, with on-chain settlement; however, they can function mainly with fungible tokens and unrestricted assets. Gold-backed tokens such as Pax Gold (PAXG) operate on DEXs through exchanges with Ethereum or stablecoins, which supply liquidity to assets usually transacted in classic financial markets (Paxos, 2024).

Centralised digital exchanges and Alternative Trading Systems (ATS) for security tokens operate as conventional exchanges, through DLT. An example in USA is the ATS tZERO, which operates under the supervision of the Financial Industry Regulatory Authority (FINRA), the platform enables security token transactions, e.g. for the AspenCoin, where trades are processed on tZERO's platform, and are then settled on-chain through token transfers between investor wallets, under platform custodianship (FINRA, 2025a). Another example is the ADDX platform in Singapore, which functions as a marketplace that connects buyers with

sellers of private-market tokens, including funds and bonds, and performs same-day settlement through DLT technology (ADDX, 2020). In 2022, the Swiss SIX Digital Exchange (SDX), in the context of Project Helvetia, conducted a digital-bond transaction, between digital bond tokens and digital CHF tokens with rapid settlement finality (BIS, SNB and SDX, 2022). The examples above demonstrate the possibility to combine the rapid transaction capabilities of DLT platforms with the exchanges' regulated environments, while protecting investors and monitoring markets.

The lifecycle management of tokenised assets requires them to interoperate with existing traditional systems. A conventional transfer agent may facilitate token redemption by burning the token and issuing a share certificate to the token holder, or an exchange may enable a broker to trade a token for a client, who does not operate on blockchain. Various pilot programs have successfully connected DLT platforms with traditional payment systems, for example by enabling ETF units to be transformed into tokens for blockchain trading. Clearing and settlement roles evolve with tokenisation. Public blockchains use network consensus to perform clearing-house functions, whereas permissioned networks rely on ordering services like Fabric or notaries like Corda, to ensure uniqueness and finality (R3, 2020).

About custody services, investors can potentially manage their assets directly or can entrust regulated digital custodians that connect to the blockchain platforms, which function similarly to the Depository Trust and Clearing Corporation (DTCC) but operate natively within wallets (DTCC et al., 2023). Qualified custodians manage tokens in isolated blockchain accounts for large institutions, like traditional custodians operate in conventional financial markets (Kapronasia, 2025b). Upon maturity of its lifecycle, a claim-representative token (such as a bond or fund share) reaches redemption status. The token's existence ends with redemption and retirement steps. When a token represents an asset like a bond or fund share, the issuer delivers value at maturity and subsequently burn the tokens. When tokens exist on a public blockchain they must undergo a final snapshot of all holders before the crypto, stablecoins or CBDC distribution, followed by token burn or redemption flagging, and a contract call that halts additional transfers. The issuer releases value payments before burning or disabling the tokens. Certain contracts automatically execute redemption and release collateral as soon as a token reaches the issuer's address (Hays et al., 2021).

Smart contracts and on-chain logic function as both middle-office and back-office operations during trading settlements, by managing confirmations and DvP enforcement, while automating post-trade reporting through mechanisms such as regulatory alerts, for addresses reaching a specified percentage of ownership, and automatic dividend tax withholding (GFMA

et al., 2025). Tokenisation combines execution with clearing and settlement, into a unified digital procedure. The standard operational flow includes five steps: creating a token with eligible collateral; secondary trading through blockchain or DLT platforms; automating corporate actions; destroying tokens at maturity or redemption; and reporting regulatory information off chain. The maximum level of efficiency can be achieved when both the asset leg and cash leg exist on the same platform, determining the crucial role of on-chain CBDCs, within the token-asset ecosystem (BdF, 2023).

4.1.5. INNOVATIVE SERVICES FOR TOKENISED ASSETS

The development of the asset tokenisation process is supported by innovative services. For instance, the custody of private keys and the provision of asset security solutions represent crucial areas within the domain of asset tokenisation. Ownership of a tokenised asset depends entirely on possession of its private key. The security of assets is directly threatened when private keys are lost or compromised (Hays et al., 2021). Institutions face risks when users manage their own keys according to the self-custody model; however, there are specialised firms that can perform custody services through third-party models. Asset management companies that act as institutional investors may demand custodial solutions that match the security standards of traditional custodial banks. Suppliers responded by developing strong security protocols such as wallets with multi-signature. Other tools analysed are the HSM, i.e. the hardware security modules and solutions based on multi-party computation. HSMs modules deliver physical storage security and cold storage reduces vulnerability to online threats by operating offline. Multi-Party Computation (MPC) solutions function by distributing key shares among multiple participants (Shaikh and Fizardo, 2025).

The major financial centres' regulatory authorities have started to establish formal rules for digital asset custody. Regulators are establishing specific requirements for custodians of digital assets such as those outlined under MiCA regulation in the EU, which include designated security and operational standards, along with capital requirements (European Parliament, 2023). The UK Financial Conduct Authority (FCA) requires that custodians demonstrate strong segregation of asset protocols, while maintaining proper cybersecurity measures and procuring insurance coverage to protect against potential risks (FCA, 2025b). The development of these regulations demonstrates how custody methods for tokenised asset are converging towards the conventional processes adopted by the financial sector. Concerns about centralisation risks continue to fuel debates surrounding the tokenised assets custodial models. The return of centralised custodians as third-party intermediaries contradicts the decentralised principles and may create potential single points of failure. Some experts argue

that both institutional investors and retail customers may adopt this innovative technology, if services remain user-friendly and operate under clear regulatory control (PwC, 2025). The future development of custody services may proceed with a hybrid methodology that merges decentralised tools (such as non-custodial wallets), with the established security and compliance measures of the traditional finance systems.

Additional supporting services have developed to sustain tokenised platforms. The alignment with regulatory obligations within the DLT systems, requires dedicated tools. Compliance solutions may enable the fulfilment of AML and KYC standards, critically important in blockchain environments, where pseudonymous transactions challenge identity verification (Udenta, 2024). Advanced software utilise on-chain analytics, alongside algorithms, to track token origins and to identify suspicious activity patterns, such as money laundering or terrorist financing. Specialised AI tools can analyse blockchain transactions, to detect suspicious activity according to the applicable regulatory requirements. Identity verification systems connect blockchain addresses to authenticated real-world identities, by employing *verifiable credentials* and related technologies. Regulatory reporting solutions may directly extract necessary reports from ledger data, to ensure the automation of compliance tasks.

Smart contract auditing is another emergent area. External auditors can perform validation checks on the code of tokenised assets, to ensure its correctness and its security, while assessing its efficiency for developers and issuers. Specialised firms conduct thorough evaluations of smart contract code, prior to deployment, to detect security weaknesses and logic mistakes, along with potential vulnerabilities. The assurance provided by formal verification methods represents an additional security layer, however the complexity of the exercise renders them difficult to adopt. Audits function as a fundamental mechanism to reduce risk for institutional entities. In tokenised environments, the risk management frameworks cover more than traditional market and credit risk concerns. Organisations need to assess security issues that arise from consensus mechanisms, while managing network congestion, and ensuring the reliability of external data sources, through oracles, as discussed by the IOSCO (2023b). Smart contracts do not have access to external data, as this feature is performed by oracles, i.e. trusted intermediaries that provide the blockchain with external information (such as asset prices, interest rates, weather data, etc.), ensuring data integrity. Fallback mechanisms, such as offline signing methods or alternative transaction pathways, may be implemented by institutions that use tokenised systems, to ensure operational continuity during blockchain network disruptions,. Organisations must perform cross-border risk assessment procedures, to navigate differing regulatory frameworks and potential legal conflicts, as tokenisation processes are not restricted by geographical and jurisdictional limits

(IOSCO, 2023b). In the next table, there is a summary of the custody models available for digital assets.

TABLE 15: CUSTODY MODELS FOR DIGITAL ASSETS

#	Model	Description
1	Self-custody models	• Users manage their private keys directly without any interference from third-party custodians. • The impact of this approach includes placing the burden of key management and security on the end user, reducing operational responsibilities, but potentially increasing user support needs, and challenges for regulatory compliance and dispute resolution, due to the lack of centralised control.
2	Custodial models	• End users delegate their private key responsibilities to third-party custodians, who handle these digital assets similarly to the management of conventional financial assets. • This approach includes increased operational and security requirements, potential counterparty risk associated with the third-party custodians, and potential pushback from users or digital currency communities that object to centralised control.
3	Multi-signature models	• The management of private keys is divided across a set number of parties, and transactions require approval from multiple entities. • There is a requirement to address operational requirements for multi-entity transaction approvals and manage coordination and timing issues during transaction execution, while ensuring secure key distribution and backup systems, through proper design considerations.
4	Hybrid models	• The system enables users to manage their private keys independently, while also offering recovery solutions to support users who lost their ability to access their keys. • Market operators may create solutions that support self-custody facilities, while maintaining user support services and recovery processes. Operators need to evaluate both security risks and their duty to manage key recovery services, while securing user key privacy.

Source: Author's elaboration.

4.2. REGULATORY FRAMEWORKS

The legal frameworks applicable to asset tokenisation, vary across different jurisdictions, and play a vital role, in determining how these technologies can develop, for the delivery of cross-borders services. The field of tokenisation began in an undefined legal space, before several jurisdictions established, or started discussing, the introduction of new sets of rules for tokenised assets. In this chapter, it is presented a critical review of the regulatory frameworks proposed by Singapore, the European Union (EU), the United States of America (USA), the

United Kingdom (UK) and Switzerland. These geographies have contributed essential information on legal adaptations, suitable to support the tokenisation process and its supplementary services, providing insights on its criticalities and on the restrictions imposed. In USA, the regulators chose to evaluate tokenised assets individually, refraining from establishing a comprehensive new legislation. Their legal framework enforces the existing securities and commodities regulations on tokens, assessing their specific features. The USA Securities and Exchange Commission (SEC) maintains that most tokens, representing investment assets, qualify as securities under the Howey test (SEC, 2024) and need to adhere to securities regulations. The legal framework in USA treats tokenised stocks, bonds, revenue-sharing tokens, and fractional real estate interests as securities, in the same way of traditional paper or electronic securities. Tokenised asset offerings (with the exclusion of cryptocurrencies classified as commodities) applied for private placement exemptions, under Regulation D (Rule 506(b) or 506(c) for accredited investors); under Regulation S (offshore); occasionally under Regulation A+ (mini public offering up to USD75m) or under Regulation CF (crowdfunding up to USD5m). The process of completing a public token offering, complying with SEC regulations, remains burdensome, despite existing evidence of successful cases, as evidenced by the INX's IPO (USD83.6m) in 2020 (SEC, 2021). The SEC Regulation D remains the preferred choice for most companies, as it allows faster fundraising, however it restricts sales to accredited investors, and it foresees a resale lock-up period of 6-12 months under Regulation D (both 506(b) and 506(c)). Retail access remains limited, in fact multiple real estate token platforms restrict their prospect market to accredited investors in the USA, with assets over USD1 million in net worth, or eligible for high income criteria. Platforms used Regulation A+ to capture interest from retail investors, for example Masterworks created fractional art investment opportunities through Regulation A+, to enable any person to purchase small portions of paintings (Masterworks, 2022). The SEC has demonstrated its ability to approve Regulation A filings for tokenised offerings, provided they comply with disclosure requirements, an initial instance was related to Blockstack obtaining Regulation A+ framework approval in 2019, for token sales, which served utility purposes (WSJ, 2019). These processes remain extensive in duration and have not become standard offers.

According to the SEC and FINRA regulations, tokenised securities must follow standard securities protocols, which means secondary trading platforms need registration as exchanges, or as Alternative Trading Systems (ATs), while broker-dealers are responsible for account management. Upon completion of their registration processes, tokenisation platforms may function as registered exchanges (or ATs), and may partner with broker-dealers' platforms, listed as Special Purpose Digital Asset Broker Dealer (SPBD), like tZERO Digital Asset Securities (FINRA, 2025a) or Prometheus Ember Capital (FINRA, 2025b). The

SEC released a joint statement with FINRA during 2019 (SEC and FINRA, 2019), to establish custody guidelines for digital asset securities, which detailed compliance methods for broker-dealers. This joint statement of SEC and FINRA was withdrawn on 15th May 2025 (SEC, 2025a). In 2023, the SEC suggested widening the scope of what constitutes an exchange, to potentially include decentralised finance platforms that trade securities tokens (SEC, 2024). The regulatory principles foresee that, across a variety of platforms, similar activities are subject to similar risks and need to respect the same rules. Regardless of its classification, any asset that functions as a security must comply with full securities regulations, including registration and anti-fraud requirements. While regulations established clear legal requirements, they also impacted the adoption of the innovation in the USA, as high compliance costs might deter projects from targeting investors across the USA, to avoid these regulations.

Federal regulations discipline the rules for exchange operations and offering procedures. Specific tokenised assets in the USA, fall under the regulatory authority of the CFTC (Commodity Futures Trading Commission), when they qualify as commodities or derivatives. Gold tokens sold to retail investors with specific structures may be subject to commodity or futures regulations (such as requiring margin or derivative features). Fully backed tokens which can deliver their assets immediately, such as gold tokens backed by physical gold, avoid CFTC scrutiny, as they qualify for physical delivery exemption. A synthetic or derivative token, including those that represent oil futures returns, may require listing on a regulated futures exchange. The regulatory system in USA requires individual examination to determine, if an item qualifies as a security under the SEC, or a commodity under the CFTC, or money, which is subject to money transmitter laws.

The Federal Reserve examined the possibility of introducing a CBDC (FRB, 2022), however an Executive Order issued by the White House on 23 January 2025 halted the development of CBDCs in USA (The White House, 2025). Without the implementation of a CBDC, the regulatory frameworks for stablecoins might establish the dependability of the cash leg for token transactions throughout the USA. Regulatory actions demonstrate oversight on tokenised offerings, with authorities prepared to intervene in case of concealed securities distribution that lack regulatory compliance. Business activities must comply with existing regulations or accept potential penalties. The regulatory landscape in the USA has been, at the time of writing, a less welcoming environment for tokenisation startups, which led agents to choose Europe or Asia for their operations. Firms prefer tokens that operate within clear and established legal frameworks. Nasdaq began tokenisation operations in 2022, with digital asset custody plans and discussed the possibility of tokenised equities after regulatory clarity.

In 2023, Franklin Templeton issued the first registered tokenised ETF in the USA (the Franklin Templeton's OnChain USA Government Money Fund) through proprietary system, using the Stellar blockchain network for transaction activity and to share ownership record, creating a connection between traditional and blockchain records (Franklin Templeton, 2024). The regulatory environment demonstrates flexibility toward innovative technologies, while maintaining established fund rules. The USA is expected to revise its regulations since discussions about a new digital asset market framework have started (The White House, 2025).

The USA adopted its first complete federal stablecoin law in July 2025, through the GENIUS Act (Guiding and Establishing National Innovation in U.S. Stablecoins), which represents the regulatory framework for digital assets pegged to the USD (U.S.A. Congress, 2025). The Act has multiple objectives, including the creation of guidelines and a dedicated licence for the issuance of stablecoins, their reserve obligations, the establishment of safeguards for investors, and the compliance with applicable financial legislation. This initiative displays a change in attitude of the American policymakers towards digital assets, and it may intend to endorse private innovation in payments; to strengthen the role of the USD as a global reserve, as a settlement method for tokenised assets; and to support the demand of USA Treasuries as reserve for stablecoins. It introduces a monetary threshold of USD10 billion in market capitalisation, to distinguish among the supervising entities. Issuers below the threshold are subject to state regulations, while those above the threshold are supervised by the Federal Reserve and the Office in charge of the Comptroller of Currency, depending on whether they are banks or non-banking institutions. Furthermore, in 2025, the SEC created a Crypto Task Force and issued the FAQ related to Crypto Asset Activities and DLT, to clarify several topics related to the application of regulations to digital assets and to develop a new approach to crypto assets (SEC, 2025b). The focus of policymakers remains on investor protection, which requires token offerings to include proper disclosure, along with secure custody and registered trading platforms. The approach to regulation in the USA evolves incrementally when compared to other areas that have implemented revolutionary changes.

The European Union has taken a more assertive approach to establish a specialised regulatory framework for crypto assets, which also encompasses tokenised assets. Two sets of legislations are relevant: the Markets in Crypto Assets Regulation (MiCA), which was issued by the European Parliament (2023) and sets the regulatory framework for the EU, and the Pilot Regime for DLT Market Infrastructures, which enables a pragmatic assessment of the new technologies (European Parliament, 2022). The DLT Pilot Regime was established through Regulation (EU) 2022/858, which became operational in 2023, to provide temporary

exemptions to market infrastructure entities, for processing tokenised financial securities in unconventional methods (European Parliament, 2022). The pilot regime, valid for six years, permits approved operators to process, through DLT platforms, stocks, bonds, and fund trading and settlement systems, while adhering to specified market cap and issuance size limits. The DLT usage benefits from exemptions to certain MiFID and Central Securities Depositories Regulation (CSDR) rules, which would normally prevent such technology from operating, such as the mandatory Central Securities Depository (CSD) involvement in settlements that can be waived for the DLT pilot regime. This framework functions as a regulatory sandbox designed for tokenised stock and bond exchanges across the EU. The pilot program intends to accumulate practical knowledge on supervised DLT testing, with the purpose of improving the EU legislation.

In 2023, the Luxembourg Stock Exchange was authorised to activate a DLT market for fund shares (Luxembourg Stock Exchange, 2025). In Spain, the Bolsas y Mercados Españoles (BME) received the approval on its DLT trading system from the Comisión Nacional del Mercado de Valores (BME, 2023). The DLT Pilot Regime may provide useful insights to reevaluate the regulatory framework. Among the principles implemented, a tokenised share retains its status as a share, while a tokenised bond shall continue to be recognised as a bond. Tokenised financial instruments must adhere to the same prospectus rules and market abuse regulations as traditional instruments. The DLT pilot allows infrastructure flexibility but maintains the strict regulations on the nature of financial instruments. Technology-neutral regulations in the EU provide significant advantages, as they could be interpreted and be applied across a variety of technologies. The EU allows transferable securities to exist, without requiring a physical form, which means an ERC-20 share may qualify as a transferable security.

The EU amended regulations such as the CSDR Regulation and the Settlement Finality Directive to explore the integration of DLT Technology. Legal guidelines in the EU require securities to be stored in book-entry form at a CSD, but stakeholders experienced some uncertainty on how to fulfil this requirement. The pilot regime exempts participants from certain rules, when their token ledger is not recognised as a book-entry system. In 2022, ESMA, the European Securities and Markets Authority, clarified that existing regulations lack explicit prohibitions against DLT, nevertheless the legal definition of security accounts may accommodate DLT through broad interpretation. The EU might evaluate changes to the CSDR that might potentially enable permanent DLT-based settlement, outside traditional CSDs, based on favourable pilot outcomes.

The EU approved the MiCA regulation in 2023 to discipline the crypto assets that fall outside the financial instruments' rules (European Parliament, 2023). The regulation applies to the issuance of different tokens (asset-referenced, utility, and e-money tokens), and it extends to service providers including exchanges and custodians. According to the MiCA definitions, asset-referenced tokens (ARTs) are tokens that represent multiple currencies and commodities or other assets, which act as stablecoins or tokenised commodity baskets, and e-money tokens serve as stablecoins for single currencies (European Parliament, 2023). There are specific authorisation requirements to protect consumers amid the necessary disclosures, including the publication of a dedicated white paper and reserve details. The MiCA excludes financial instruments from its scope, since these instruments need to comply with existing securities' regulations, but it remains crucial as it establishes legal guidelines for tokenised assets not corresponding to conventional asset classifications (for example, a tokenised gold coin may fall under MiCA's asset-referenced token category and must adhere to these regulations). The MiCA offers clear regulatory guidance to crypto exchanges within the EU, on how to list tokens for real assets that aren't shares of a company (for instance, a token representing an asset that isn't a security is governed by MiCA, if it doesn't fall under MiFID regulations).

The MiCA framework establishes direct regulatory controls over stablecoin issuers within the EU. An issuer of a euro-backed token needs to obtain authorisation as either an e-money or a credit institution and must comply with capital requirements and investor protection rules. The development of a stablecoin market, both robust and regulated within the EU, may create secure cash options for tokenised asset trading, until when a digital euro CDBC may be launched. The MiCA also addresses the public offering of tokens, as in the EU, a token issuance to the public, even if remains below a specified threshold, requires the presentation of a crypto-asset white paper to the EU regulators, albeit it may be exempted from the publication of a full prospectus (unless it qualifies as a MiFID II instrument). Companies planning the retail sale of tokenised commodities, may benefit from a defined compliance route. The EU regulatory bodies distinguish between crypto assets classified as financial instruments, which require full regulatory compliance and those that fall under the MiCA regulation. The EU has aimed for tech-neutral legislation for financial instruments on DLT but remains open to necessary adjustments.

Germany, Luxembourg and France implemented frameworks to enable blockchain-based issuance of unlisted securities. Germany approved, in 2021, the Electronic Securities Act (Gesetz zur Einführung elektronischer Wertpapiere), to allow bearer bonds to be issued digitally (BaFin, 2021b) and to expand laws to include stocks and fund units (BaFin, 2023).

The new German legislation eliminates the requirement for physical global certificates, when using DLT or electronic registers that have been enlisted with BaFin.

Crypto exchanges and custodians need to adhere to identical legal restrictions that apply to traditional financial institutions, including KYC and transaction monitoring requirements. All platforms, trading tokenised assets to the public, must conduct proper KYC checks on users. Crypto transactions exceeding specific thresholds must adhere to the Travel Rule, when performing transfers of assets. The Financial Action Task Force (FATF), to promote legality across digital exchanges and to combat financial crime, created the Travel Rule that impose to Crypto Asset Service Providers (CASPs) the duty of the determination and communication of the origins and destinations of transactions, made using crypto assets, when above a defined threshold, which in the EU was set to zero in 2024 (FATF, 2024). The EU's regulatory approach is one of the most comprehensive, targeting consumer protection and balancing innovation with risk mitigation. The EU has developed custom regulations for emerging technologies (MiCA and DLT Pilot), enforcing current investor protections rules, and has recently reviewed the other relevant legislations (such as the MIFID II and MiFIR). Tokenised bond issuances have been performed from entities such as the EIB and European banks through national law support (EIB, 2022), while crypto firms have a clear regulatory framework for their licensing requirements and to conduct experiments under the DLT Pilot Regime, instead of dealing with legal uncertainty.

The UK has pursued active evaluations of crypto-assets and tokenisation regulations, embracing a regulatory approach that combines common law adaptability, with incremental regulation changes and pilot testing, while holding a middle ground between the USA and EU. The UK showed openness toward the possibility to modify fundamental principles in its legal system. The Law Commission issued a comprehensive report, which offered guidelines for the legal treatment of digital assets, by introducing data objects as a new private property category for crypto-assets, and by advocating statutory reforms, to acknowledge tokens used as collateral (UK Law Commission, 2024). In 2023, the UK government announced intentions to modify the Electronic Transactions Act, to enable DLT share registers. The UK legal provisions advance towards recognition of tokenised assets, alongside secure ownership records (UK HM Treasury, 2023). The Financial Conduct Authority (FCA) implemented the *same activity, same risk, same rules* approach of the FSB, in their regulatory framework. In 2019, the FCA released guidance to classify tokens into three categories including security, e-money, and unregulated (known as utility/exchange tokens). The Financial Services and Markets Act 2023 (FSMA) mandates specific requirements such as prospectuses and authorised intermediaries for security tokens, which hold rights across shares and debt (UK

Public General Acts, 2023). The UK government implemented in 2023 the Digital Securities Sandbox (DSS), to enable DLT infrastructures, to function under a flexible regulatory system that mirrors the EU DLT Pilot Regime. The sandbox provision in the FSMA became law in 2023 and allows stock exchanges to apply for temporary exemptions from normal CSD regulations to operate DLT settlement systems (UK Public General Acts, 2023).

The Bank of England and FCA share responsibility for supervising the process. Through a system inspired by the EU DLT Pilot Regime, the UK plans to develop tokenisation projects, which may allow exchanges, like the London Stock Exchange (LSE) and Aquis Stock Exchange, to test new trading venues and settlement methods for tokenised instruments. However, the UK market has experienced only a few occurrences of tokenised securities trading, at the time of writing. After exploring blockchain applications for post-trade processes, the LSE has not yet made any significant public launch in this area, despite the fact that in 2023, the LSE Group revealed plans to create LSE Digital Markets for trading tokenised assets (Noonan and Stafford, 2023). The UK regulators maintain broad classification categories, while determining whether a token qualifies as a Specified Investment, under the Regulated Activities Order. Shares and bonds represented by tokens that qualify as specified investments are subject to regulatory standards. A stablecoin can be considered e-money, if it corresponds to the e-money definition (as stored value redeemable at par, not designated as a Specified Investment). The UK government may regulate stablecoins, by placing systemic stablecoins under control of the Bank of England (BoE), and other stablecoins under the FCA regulation, to include token-based payment instruments, through the extension of Electronic Money regulations, or Payment Services regulations. The HM Treasury published near final draft legislation that will also bring the issuance of stablecoins issued in UK, under the Financial Services and Markets Act 2023 (UK Public General Acts, 2023).

The FCA launched CP25/14 and CP25/15 to seek feedback on the draft rules and guidance related to the issuance of a qualifying stablecoin and safeguarding qualifying crypto assets (FCA, 2025a; FCA 2025b). At the time of writing, cryptocurrencies and NFTs exist without regulatory oversight, apart from AML requirements. The FCA has indicated that an NFT, when representing a unique asset, might fall under regulatory scrutiny, if it becomes part of an offering, as fractional NFT have been classified as potential collective investment schemes. The UK might categorise fractional art tokens, as collective investment schemes, when they function as pooled investments. Since 2023, UK regulations mandate that promotions for crypto assets must be conducted by authorised firms, adhering to strict guidelines, which include risk warnings (UK HM Treasury, 2023). The primary goal of these measures is to safeguard consumers from widespread crypto frauds. Any marketing of a token offering in the

UK requires careful consideration, as regulated securities require a dedicated prospectus or an approved exemption, while unregulated tokens may require authorised firm approval, to avoid falling under the financial promotion restrictions.

The FCA's focus remains on preventing issues with speculative crypto assets, while the BoE continues its development work on a sovereign CBDC, i.e. the Digital Pound. In 2023, a consultation outlined a potential issuance of a Digital Pound using a dual-provider system, where the Bank operates the core ledger and the private sector entities might be entrusted to manage digital wallets (BoE, 2023). The BoE demonstrates its readiness for tokenised assets through methods that enable their settlement using central bank money. The BoE upgraded the Real Time Gross Settlement (RTGS) system, by developing a synchronisation feature for atomic settlement, between RTGS and external systems based on DLT technologies, which enables DvP for central bank money in RTGS and for tokens on DLT systems (BoE, 2025). The future may see the approval of tokenisation initiatives, within the Digital Securities Sandbox (DSS), under the shared responsibility of the FCA (for trading venues) and the BoE (for central security depositories), through pilot programs and an extension of the regulatory boundaries to include stablecoins and crypto trading (BoE and FCA, 2024), while regulators may improve the legal guidance for UK companies, through updates to laws or new guidelines.

Over the past years, Singapore encouraged innovation initiatives, related to blockchain and asset tokenisation. Tokens deployed as capital markets products (securities and derivatives) are regulated by the Singapore Securities and Futures Act (SFA). Digital tokens, when classified as capital market products, have the same regulatory treatment. The Monetary Authority of Singapore (MAS) identified digital tokens as subject to the SFA, when they represent equity or debt (MAS, 2020). A Capital Markets Services license is required to enable platforms to process security tokens transactions. The MAS has operated a FinTech Regulatory Sandbox, where entities could test their new products, with certain regulatory exemptions. Public offering regulations remain consistent with global standards, as demonstrated by the iSTOX case (later renamed as ADDX), which received approval in 2020, and became the first security token platform to perform testing in the MAS FinTech Regulatory Sandbox (ADDX, 2020). The MAS demonstrated prompt support and collaborated to the launch of Project Ubin (MAS, 2025b), which examined DLT applications for payments and securities, before proceeding to DvP trials on various blockchain networks and cross-border CBDC payments.

The MAS initiated Project Guardian in 2022, to explore tokenisation and DeFi use cases with financial industry partners, through controlled pilot testing for risk assessment (MAS, 2025a).

Under the regulatory guidelines, participants accessed permissioned liquidity pools, which allowed the access only to verified users, through a trust framework. In 2023, the MAS widened the scope of Project Guardian to include additional use cases, namely, the tokenisation of wealth management products, and of trade finance assets (MAS and BIS, 2023). Through these research projects, the MAS demonstrated to industry stakeholders its openness to innovative solutions. The Singapore's Payment Services Act (PSA), launched in 2019, mandates that digital payment token (DPT) service providers, operating as crypto exchanges, brokers, or custodians are subject to licensing requirements. The regulation includes exchanges which list tokenised assets, not classified as securities. The exchanges need a license to list tokenised gold coins in Singapore, as they are considered DPTs, instead of securities. The PSA requires adherence to AML/CFT guidelines and technology risk management principles among other requirements (Parliament of Singapore, 2019).

The MAS processed several applications and licensed multiple companies including Crypto.com, DBS Vickers, and Paxos (Fintech Singapore, 2024). The trading infrastructure in Singapore for non-security tokens operates under clear regulations, providing stability to companies aiming to build token markets in the country. The MAS established a regulatory framework for stablecoins pegged to either the SGD or other currencies of relevant countries, that maintain a minimum threshold in value of SGD5 million. Issuers need to fulfil various requirements, including prudential standards and full asset backing with low-risk assets, alongside redemption at par value (MAS, 2023). The framework, which covers tokenised bank deposits and stablecoins, may support investor protection. Singapore tested wholesale CBDC systems through Project Ubin and has not yet launched a retail CBDC, as the MAS has found current electronic payment systems sufficient and continues to assess the potential introduction of a CBDC (MAS, 2022).

A Singapore court established a precedent in 2022, by acknowledging cryptocurrency assets as property, through the issuance of a freezing injunction on NFTs, which demonstrated legal openness to classifying digital tokens as property (High Court of the Republic of Singapore, 2022). Singapore defines its regulatory approach as technology-neutral and activity-centred, in how it examines actions such as issuing securities and trading facilitation (MAS, 2024). Through Project Guardian and other initiatives, the MAS works closely with industry representatives to develop the future regulations (Guardian Foreign Exchange Industry Group, 2025). Singapore might integrate standards for smart contract auditing and operational oversight into its regulatory framework, as it already mandates technological risk management compliance for banking activities. Thanks to its balanced approach Singapore has emerged

as a leading country for tokenised asset issuance and for enabling their trading in a regulated environment.

Switzerland has established a welcoming regulatory environment for tokenisation, through its flexible civil law for securities and a pragmatic regulatory approach. During 2021, amendments to multiple laws entered into force in Switzerland, under the DLT Act (Swiss Federal Council, 2021). The Swiss Code of Obligations was amended to introduce the legal recognition of a new security form, called Registerwertrechte (Uncertificated Register Securities). Securities, which function as claims or membership rights, are formed through entries in a DLT-based register that fulfils specific conditions, i.e. the register's integrity remains protected from unidirectional changes and creditors maintain access to information. The register serves as the exclusive platform for exercising and transferring the assigned rights. The system provides complete legal recognition to ledger-based securities, so that shares or bonds recorded on blockchain technology receive equal status with traditional securities, documented through certificates or book entries

The regulation allows Swiss companies to issue shares and bonds as tokens with full legal certainty, establishing the tokens as the definitive proof of ownership. The Swiss National Bank (SNB) issued a series of new regulations to attract new licensed companies (SBA, 2022). The Swiss legislation authorised the segregation of crypto assets during bankruptcy proceedings, while detailing custodian responsibilities and strengthening the enforcement of digital asset pledges, resulting in an extensive legal transformation. A new license category for crypto trading facilities was established under the Swiss Financial Market Supervisor (FINMA, 2025). Under the Swiss legislation, asset tokens representing either debt or equity claims, on an issuer or asset claims, are classified as securities, and necessitates a prospectus for public offerings. The Swiss Financial Services Act (FinSA) requires tokens representing shares to meet the same prospectus requirements as traditional share offerings (Swiss Federal Council, 2018). In 2020, Switzerland adopted a new prospectus regulation, aligned to the EU standards, which requires token offerings of securities to either be exempt under private placement rules, or to launch with a regulatory-approved prospectus (FINMA, 2020). Sygnum Bank used the new DLT regulations to tokenise its shares and to conduct a public offering, after obtaining a regulator-approved prospectus, becoming the first bank to publicly issue shares in token form (Sygnum Bank, 2020b). In this way, the Swiss authorities granted banking licenses to crypto-specialists, like Sygnum, enabling the trade of tokenised securities within established banking and securities dealer regulations. In 2021, after receiving operational approvals the SIX Group established SIX Digital Exchange (SDX) to function as an exchange and a Central Securities Depository for securities in DLT systems (SDX, 2021b).

SDX maintains a limited participant base, primarily composed of member banks, while having the capability to list tokenised bonds and various other assets. SDX first listed a digital bond from SIX, its parent company, and then went on to list additional bonds from UBS and other entities (SDX, 2021b). Another example is BX Digital AG, which operates as a crypto exchange that lists asset backed tokens (such as stock basket tracking tokens), which function as structured products, under established exchange regulations (Baker McKenzie, 2025). Thanks to clear rules and reasonable licensing requirements, several projects were launched in Switzerland. FINMA assigns regulatory status to stablecoins and payment tokens, based on their similarity to currency, as either money transmission services, or banking products, depending on their structure. Under their banking licenses, Swiss banks can obtain the ability to issue their own stablecoins, as demonstrated by Sygnum which released the DCHF stablecoin fully secured by CHF deposits (Sygnum Bank, 2020a). Switzerland maintains rigorous AML regulations that incorporate the Travel Rule for cryptocurrency transactions (with zero threshold), and FINMA actively enforces these regulations resulting in operational challenges, including a mandatory identity threshold of 1,000 CHF in related transactions during a 30-day period for decentralised exchanges (FINMA, 2023).

The existing tax environment maintains its favourable conditions, particularly for capital gains and for the creation of utility tokens. The Ethereum Foundation and numerous Swiss crypto firms operate in Switzerland, thanks to its business environment. The BIS collaborated with SNB and SIX on Project Helvetia (BIS, SNB and SDX, 2022; BIS, 2023h), to examine wholesale CBDC operations through SDX, demonstrating public sector participation. Switzerland offers one of the most developed legal frameworks for tokenised assets, which includes explicit DLT securities laws, and operates with several licensed infrastructure providers. The jurisdiction has become a favoured location for initiating security tokens. Established financial institutions and startups operate on tokenisation, evidencing a robust ecosystem. This method has been proven effective through successful issuances in tokenised bonds and equity, alongside various private market deals. Clear and balanced regulations with developed ecosystems may foster business conditions favourable to the tokenisation of assets and may attract companies, currently facing restrictive or unclear regulatory landscapes across the world.

4.3. CBDCs AS SETTLEMENT STANDARD FOR TOKENISED ASSETS

Asset tokenisation achieves efficiency when digital money is on the same or interoperable ledgers to enable atomic settlement. The financial industry has explored cryptocurrencies,

regulated stablecoins, backed by actual assets, and tokenised deposits, which represents commercial bank money, as alternative tools for atomic settlement on DLT systems, to substitute direct central bank liability (BIS, SNB and SDX, 2020; FSB, 2019). Private stablecoins, such as Tether's USDT (S&P Global, 2024b), or Circle's USDC (S&P Global, 2024a), along with cryptocurrencies, provide investors and market players with digital assets accessible for settlement. The analysis of these native digital assets reveals important insights into their roles, and limitations in settling tokenised asset transactions. Cryptocurrencies represent a settlement option for platforms with native digital currency capabilities (such as Ethereum) and correspond to unpegged volatile digital assets. The excessive instability of cryptocurrencies has prevented them from serving as reliable settlement currency for tokenised trades related to real assets, which are usually denominated in fiat currencies.

Settling tokenised bond trades in Bitcoin (BTC) may be impractical, as the BTC price change between the trade and settlement might alter the payment value. Cryptos have no issuing authority to assure redemption value, as their worth relies entirely on market dynamics and network effects. Their nature may align them closer to speculative investments, rather than to trusted payment systems. Bitcoin achieves final settlement, when mined transactions on its blockchain become irreversible after confirmation, however this process suffers from slow transaction speed, and it requires waiting time for multiple blocks to be completed, to minimise reorganisation risk, exposing transactions to value fluctuations during the confirmation time. Besides, the legal and compliance issues remain significant, as the combination of anti-money-laundering regulations and other compliance issues may prevent regulated institutions from processing securities transactions through cryptocurrencies.

Pilot projects have tested the use of cryptocurrencies as intermediary assets. The use of Ripple's XRP in remittance pilot projects has shown potential (Ripple, 2025), but it might not fully meet requirements for widespread securities settlements. Cryptocurrencies may serve effectively for tokenised asset settlement only for specialised applications, in crypto-native environments, such as trading crypto assets for Ether on the Ethereum blockchain. In their current forms, cryptocurrencies may not exhibit the required stability and compliance standards required. Policymakers and national monetary authorities have consistently disregarded the use of cryptocurrencies for post-trade settlement with real world assets. Over the past years, the crypto market suffered downturns and multiple exchange failures, the crypto market failure in 2022 demonstrated that building essential financial market operations, basing them on unstable crypto tokens, may pose substantial risks (BIS, 2023e).

Stablecoins serve as digital tokens, whose value remain fixed, by maintaining a unique correlation with fiat currencies. These digital assets function as fiat proxies for crypto trading and for selected international payment transactions. Tether's USDT, a stablecoin pegged to the USD with a market capitalisation above \$181 billion as of 23rd October 2025, processes a significant part of cryptocurrency trade settlement and it can exemplify the recent growth of the stablecoins' market, albeit its value stability has fluctuated over time (CoinMarketCap, 2025a). The operational features of stablecoins partially overlap with those of CBDCs since they enable continuous digital payments and can coexist alongside tokenised assets on DLT technologies. In the absence of CBDCs, stablecoins have responded to the market requirements for digital assets to settle transactions. However, there are important drawbacks to consider, as stablecoins do not represent money from central banks, or the traditional banking sector, and their design features exhibit considerable differences in the levels of trustworthiness (Adachi et al., 2022).

Stablecoins represent obligations from private entities and are traditionally secured by reserves, however the transparency standards along with the legal protections of their reserves may display significant variations between issuers (Garratt and Shin, 2023). Historical evidence shows that stablecoins may lose their peg value, when investors question the quality of reserves, or when they face redemption rushes. A BIS study on stablecoins found out that none of those analysed, maintained a perfectly stable parity with the selected fiat currency (Ahmed, Aldasoro and Duley, 2024). Empirically, it is possible to observe that stablecoins may not maintain a perfect peg during tense market conditions, as even the best issuers experience minor off-par trading ranges during stressful times. For instance, USDT and USDC have shown minor fluctuations from its USD1 value, while facing continuous scrutiny about their backing reserves (Ahmed, Aldasoro and Duley, 2024). When asset settlement processes use stablecoins, they encounter valuation risk since, in case of crisis, the USD1 received might not be worth the same amount. Final settlement for stablecoin transactions happens, when they are exchanged for central bank money through bank redemption. Until redemption, investors hold a private liability.

A stablecoin payment's finality exists solely in the stablecoin ledger, which does not offer the legal finality provided by central bank settlements and users might be left with uninsured exposure, if stablecoin issuers collapse. Stablecoin systems operate without the credit backing and the liquidity mechanisms, which normally support traditional banking activities. An analysis revealed that issuers of stablecoins typically do not provide credit lines or intraday loans (Ahmed, Aldasoro and Duley, 2024). All transfers require participants to prefund them, which results in liquidity being tied up and in an increase of the cost of large value

transactions. A CBDC or regulated payment system may allow participants to access small overdrafts or intraday credit for payment facilitation. Without access to credit facilities, stablecoin systems face delays in settlements and may require greater liquidity buffers. Furthermore, the stablecoin market poses concentration and stability risks, as it is heavily influenced by a small number of issuers, and this may create critical vulnerabilities.

The tokenised assets market would face significant disruption in case of a stablecoin collapse, like the one experienced by TerraUSD in 2022 (Krause, 2025). According to Ahmed and Aldasoro (2025), in March 2025, stablecoins pegged to the USD reached more than USD200 billion in market capitalisation, with an estimated market size of over USD1 trillion before the year 2030. Stablecoins pegged to the USD are assuming an importance comparable to major investors, to the point that inflows and outflows to stablecoins might impact the 3-month T-bill yields (Ahmed and Aldasoro, 2025). In response to these risks, regulators have implemented stricter controls for stablecoins used in systemic markets, as they now must ensure minimal credit and liquidity risks, and they need to adhere to similar safeguards of essential payment systems (U.S.A. Congress, 2025). Regulatory measures to enhance stablecoin stability might force stablecoins to function like money market funds to ensure safety (European Parliament, 2023). This raises doubts about the necessity of stablecoins, when CBDCs or tokenised bank deposits may become widely accessible. In asset tokenisation, stablecoins offering digital settlements on DLT platforms, may be seen as interim solutions, that may introduce new risks when used extensively, in critical financial markets. The security of central bank money cannot be replicated by these instruments; despite they serve similar requirements. The credit, liquidity and operational uncertainties associated with stablecoin transactions may deter financial institutions from using them for high value tokenised trade settlements.

In the absence of CBDCs, the cash component of current tokenised asset trading may depend on private stablecoins, such as USDC (S&P Global, 2024a), bank tokenised funds such as Kynexys Digital Payments (JP Morgan Chase & Co., 2025) or cryptocurrencies used on public chains such as XRP (Ripple, 2025). Despite functioning effectively, these instruments present credit risk, including stablecoins, which represent issuer obligations, lacking universal accessibility and trustworthiness. Researchers observed that regulated stablecoins may remain as stand-ins for smart contract support, until when CBDCs may be able to process transactions directly, enabling native smart contract capabilities (BIS, 2022a).

Central bank money may eliminate credit risks, and it may serve as the fundamental settlement asset within modern financial systems to settle interbank obligations. Digital currencies issued by central banks can enable secure cash-on-ledger settlements for

tokenised assets, under central bank protections. CBDCs may function as a trusted and recognised medium of exchange in tokenised markets, while reducing settlement risks and the complexities faced with commercial bank money and stablecoins (BIS and CPMI, 2024). CBDCs provide immediate settlement finality, making fund transfers between parties more efficient and lowering credit risks for counterparties, according to recent pilot projects across Europe, Asia, and North America (BIS et al., 2020).

Policy papers emphasise that wholesale CBDCs need specific legal tender statute, and guidelines on the interoperability with current RTGS systems (BIS and CPMI, 2019; BdF, 2023). Research findings from dedicated international projects, such as Project Helvetia (SNB, 2025; BIS, 2023h) and Project mBridge (BIS, 2024) indicate multiple areas where CBDCs can enhance the asset tokenisation process. Firstly, the use of central bank money, as risk free settlement asset, may eliminate the dependence on stablecoins, reducing Herstatt type risks, where a party deliver the foreign exchange due for a trade, and it fails to receive the currency payment from the correspondent bank (ECB, 2007). Secondly, through atomic DvP and PvP transactions, smart contracts may enable the simultaneous transfer of tokenised securities and CBDC to achieve true settlement finality, without intermediated netting. Thirdly, intraday programmable CBDCs may enable automatic escrow, lending and rehypothecation, leading to reduced collateral requirements, according to the Guardian Foreign Exchange Industry Group (2025). This chapter analyses the contribution of CBDCs to the settlement process of tokenised markets, evaluating the new capabilities introduced, their benefits and along with difficulties or aspects of complexity to be considered.

The programmability feature of CBDCs could enable automated payments, based on smart contracts (Deloitte, 2024). Selecting between different settlement models may create major impacts on the market structure and on the distribution of risks. For instance, the introduction of a wCBDC might alter the interbank market dynamics, diminishing commercial banks' roles in settlement processes. A broad adoption of rCBDCs might have substantial effects on bank deposits and their ability to lend money. The CEPR (2021) identifies wCBDC as a valid solution for settling digital securities tokens. The exchange of wCBDC for tokenised assets, on either the same or on interoperable DLT platforms, would enable the achievement of true atomic settlement. Several central banks, including China, Switzerland, and the Eurosystem, are testing wCBDCs to ensure that the monetary systems could keep pace with tokenised securities.

According to the BIS (2023h), Project Helvetia undertaken in Switzerland with SIX and the Swiss National Bank (SNB), alongside with Project Jura, involving France and Switzerland

with the BIS Innovation Hub (BdF, BIS and SNB, 2021), demonstrated the successful settlement tests of tokenised assets against wCBDC. Projects Helvetia and Jura served as trials to assess cross-border tokenised securities trades, through DLT platforms. Project Helvetia achieved settlement of tokenised securities on SDX with tokenised CHF money, by connecting this process to the central bank's payment system (BIS, 2023h). In Project Jura, the Banque de France created a tokenised Euro wCBDC (BdF, BIS and SNB, 2021), while for Project Helvetia, the SNB developed a tokenised CHF CBDC on a unified platform (based on a Corda network), to test a transaction, where a French bank acquired a Swiss digital bond and paid using CBDC in Euro, alongside atomic PvP currency exchange mechanisms (BIS, 2023h). The results demonstrate that wCBDC functions as a valid settlement mechanism for tokenised markets, by enabling atomic cross-border settlements and delivering tokenised assets in seconds, instead of the days needed by traditional systems with multiple intermediaries. These projects ascertained the singleness of money, when using CBDC for the settlement of digital assets, representing the highest quality settlement asset on DLT platforms according to BIS (2023h).

The implementation of wCBDCs may lead to the use of central bank money for DvP settlements for securities on DLT platforms. Through the tokenisation of both assets and CBDC on compatible ledgers, the execution of atomic swaps (DvP) between CBDC and tokens becomes achievable. A CBDC could immediately settle a bond traded on a token exchange. Central banks promote this approach for maintaining financial stability, as it could prevent fragmented token markets from splitting liquidity, and it could mitigate the dependence on private coins, subject to default risks. According to the BIS (2023h), a unified ledger may enable central bank money to work alongside commercial bank money and tokenised assets on shared platforms, facilitating more efficient payments and asset exchanges. The design of a wCBDC involves important choices concerning its technological architecture (that can be based upon single or multiple ledgers), the access control (determining which entities will manage it), and ensuring interoperability with existing legacy systems (interfacing tokenised assets and RTGS or instant payment systems).

CBDCs may drive wider digital transformation in financial markets by connecting decentralised asset ledgers with conventional fiat-based systems. The settlement of token trades through CBDCs results in final settlement with central bank money, which represents the most secure standard. The integration of tokenised trade documents with CBDC payments may enhance settlement efficiency for securities, derivatives margin payments and cross-border trade finance flows, while accelerating the value chain and decreasing bureaucratic requirements and operational risk (WEF, 2025). Retail CBDCs can facilitate user interaction with tokenised

assets by expanding accessibility and by simplifying the process for users. CBDC wallets may let individuals purchase tokenised securities or assets directly through their banks. The adoption of these types of facilities may eliminate obstacles for channelling funds into DLT networks. Currently, retail investors who want to purchase tokenised bonds on a public chain need to obtain stablecoin or to transfer money to a crypto exchange, but with CBDCs, they might be able to make such transactions through their CBDC wallets.

The introduction of rCBDC could lead to broader participation from retail investors in tokenised markets, via the provision of a direct access. In fact, the establishment of rCBDC may enable ordinary citizens to invest directly in tokenised assets, while receiving income streams through CBDC wallets. Through retail fractional ownership platforms people can make small investments in tokenised financial securities, like bond coupons. Investors may be able to collect their asset income on their CBDC wallets, in an equivalent way of receiving corporate bond interest in their bank accounts. This approach might merge investment and cash accounts for consumers, consolidating all funds into a single wallet. Combining investment and cash management in one wallet, and supporting micro investment scenarios, such as automatic purchase plans, could enable users to make automated small-scale investments into tokenised assets, with minimal transaction costs.

Another way to settle digital assets through CBDCs, may be to ensure interoperability across platforms, via interfaces and bridges. Cross-currency token trades may be facilitated by settlements through multiple CBDCs. The BIS Innovation Hub has partnered with the central banks of China, the UAE, Thailand, and Hong Kong to investigate cross-border CBDC settlement schemes through the mBridge project (BIS, 2024). The project mBridge shows how instant multi-currency token exchanges can occur through PvP cross-border CBDC transactions (BIS, 2024). Cross-border CBDC trade settlement solutions could interface asset exchanges. In this scenario, an overseas investor who possess Currency 1 CBDC and wishes to purchase a tokenised security denominated in Currency 2 CBDC, can use a smart contract to perform a PvP atomic swap of Currency 1 CBDC, to Currency 2 CBDC, at a set FX rate, and then execute DvP swapping of Currency 2 CBDC into the security token required. The use of multi-leg atomic settlements has the potential to streamline cross-border transactions that presently depend on correspondent banks and encounter time zone delays.

The integration of tokenised assets and digital money enables developers to design transaction flows that execute both simultaneously. In a tokenised bond system, the coupon payment can happen automatically through CBDC, by debiting the CBDC account of the issuer and crediting the wallets of token holders, on the coupon payment date (Cisar et al., 2025).

Token-holders may not require intermediary assistance, since their transactions settle through central bank money. Smart contracts programmed for coupons and dividends can automatically schedule CBDC distributions, while instruments for conditional payments can incorporate triggers to release CBDCs to the entitled owners (Cisar et al., 2025).

The simultaneous tokenisation of assets and money enables the programming of integrated financial flows. For instance, smart contracts can use CBDC for conditional payments, such as tokenised letters of credit, which may release CBDC to exporters, when goods delivery confirmation is received from an oracle. Additionally, when considering a tokenised bond coupon, paid automatically through CBDC on the coupon payment date, issuers could program their wallets, to automatically deduct CBDC funds from their accounts and to distribute CBDC credits to token holder accounts, based on ownership of shares (Cisar et al., 2025). The use of central bank money gives token holders direct payment assurance, without requiring any intermediary to provide guarantees. Although stablecoins may perform these functions, CBDC usage would provide banks and enterprises with the confidence they lack, when using private coins for large transactions. Conditional payment instruments that are designed to release CBDCs following oracles' delivery confirmation, become feasible solutions for corporate entities concerned about private cryptocurrencies' risks (Schär, 2021).

Researchers are studying systems where banks can instantly pledge and un-pledge their tokenised assets, using unified or interconnected ledgers. Banks may enhance intraday CBDC collateral and liquidity management, by using smart contracts to pledge tokenised assets, such as government bonds, and then automatically return the collateral, once the overdraft is settled (WEF, 2025). The use of tokenised government bonds, as collateral through smart contracts, can improve central bank discount windows (the provision of funds to banks during the day), by enabling additional intraday CBDC liquidity. Banks may use tokenised assets, such as tokenised government bonds, to execute collateral transfers through CBDC. When experiencing intraday liquidity shortages, a bank could create digital tokens of its assets, to use them as collateral for borrowing CBDC through a repo arrangement with the central bank, based on smart contracts. While this remains speculative, monetary authorities might consider more adaptable collateral mobilisation strategies, to ensure smoother functioning of payment systems.

A potential architectural solution could foresee the deployment of a unified ledger, to allow tokenised governmental bonds, owned by banking institutions, to be automatically pledged for CBDC overdrafts and released upon repayment. The possibility of frictionless conversion between CBDCs and tokenised assets could improve banks' reserve management and affect monetary policy transmission, while central banks examine safeguards, such as rCBDC

conversion limits to prevent disintermediation risks (CEPR, 2021). CBDCs may act as catalyst for tokenised assets, as they may deliver the required trust and settlement finality for atomic DvP operations, while reducing credit risk and enabling innovative programmable financial products. Settlement finality through central bank money decreases settlement periods for securities and derivative margin payments, as well as for cross-border trade finance payments (which may execute against tokenised trade documents), while lowering operational risk. The value chain of financial transactions may accelerate thanks to this approach, while potentially lowering both liquidity requirements and operational risks. The integration of DLT platforms with traditional systems may result in operational efficiency improvements, while presenting integration complexities. The progression towards CBDC integration with token markets becomes tangible through pilot projects in Europe, Switzerland, Hong Kong, and Singapore.

The use of a wholesale CBDC on the SIX Digital Exchange for Project Helvetia, enabled the settlement of tokenised securities through central bank money (BIS, 2023h). The initiative demonstrated tangible benefits, reducing operational risks, alongside shorter settlement periods and built-in compliance verification. Project Dunbar represents another relevant case which examined cross-border payment systems, utilising multiple wCBDCs from different jurisdictions (BIS et al., 2022). The project demonstrated the practical possibility of technical interoperability, enabling transactions across different CBDCs to run on a single platform, without requiring additional intermediaries. The results demonstrated the necessity for standard governance procedures and strong anti-money-laundering measures, along with synchronised macroprudential policies, amongst the central banks involved. Divergent CBDC tech stacks may introduce fragmentation risks for markets that require harmonisation and interoperability. The merging of asset transactions with CBDC demands solutions to address emerging data confidentiality concerns. Clarity is necessary to establish the finality of the transactions, i.e. the point at which a DLT-based CBDC transfer becomes irreversible, similarly to the specifications of the payments executed through RTGS systems.

Practical experimentation provides valuable insights. With Project Venus, the EIB issued multiple digital bonds on Ethereum and private blockchains, to test DvP settlement through CBDCs, or tokenised commercial bank money (EIB, 2022). Forge, a licensed subsidiary of Société Générale, issued tokenised structured products and bonds, such as Security Tokens, on Tezos and Ethereum platforms to demonstrate a drive towards the commercialisation phase of digital assets (Société Générale, 2020). The German company Siemens issued a digital bond worth EUR60 million on the Polygon blockchain in 2023, in line with the Germany's Electronic Securities Act (Siemens AG, 2024). The ADDX platform in Singapore enables fractional asset investments across various domains, including commercial real estate

projects to make investments more accessible (ADDX, 2020). A study by Kreppmeier et al. (2023) analysed the USA real estate tokens. Despite observing increased investor participation and emerging secondary market liquidity, the researchers noted limited portfolio diversification among token holders. Hamilton Lane, a private equity firm, tokenised several private equity funds through dedicated platforms (such as Securitize or Republic), to make them more accessible to small investors and to enhance secondary market options (Ledger Insights, 2024a).

As interim solution, financial institutions have also explored the tokenisation of commercial bank deposits, which represent claims on commercial banks in token form, which can be redeemed on par with central bank money. Tokenised commercial bank deposits have been proposed as a secure alternative to stablecoins, as they operate within the established two-tier monetary system, where banks issue money as deposits, under regulatory supervision. Tokenised deposits preserve banking system's integrity through parity and credit protection, while stablecoins may not guarantee them. The settlement of tokenised deposits between banks takes place through central bank money (reserves), which makes tokenised deposit an additional instrument to wCBDCs, instead of an alternative. In fact, wCBDCs and tokenised deposits together may complement each other, as banks create digital tokens from their liabilities to enable customer transactions, and these tokens can either interoperate with or be converted into a wCBDC for interbank settlements (BIS and CPMI, 2024).

The development of tokenised sovereign currency may become the settlement method of choice for tokenised assets. CBDCs integrate digital token features such as speed and programmability into central bank money, to ensure stability and trustworthiness. When accounting for these factors, CBDCs and tokenised central bank money may be a better fit for asset settlement, when compared to stablecoins or cryptocurrencies. Cryptocurrencies display excessive volatility alongside lack of public trust establishment, and poor fiat value linkage, rendering them unsuitable for mainstream tokenised market settlement functions. Stablecoins act as digital substitutes for fiat currency tokens, but their credit and stability risks threaten to disrupt settlement security. CBDCs integrate digital ease of use with central bank money protection, which position them as ideal instruments for operations in tokenised asset markets. The evaluation of available options indicates that CBDCs, alongside tokenised bank deposits with central bank backing, stand as the most reliable options for secure settlement mechanisms. In the following table, a comparison shows how CBDCs, stablecoins and cryptocurrencies perform the settlement mechanisms for tokenised asset.

TABLE 16: COMPARISON OF CRYPTOCURRENCIES, STABLECOINS, TOKENISED DEPOSITS AND CBDCs

Asset	Legal Nature	Issuance mechanisms	Backing Assets	Value Stability	Settlement Finality and Risks	Market scenarios
Crypto	- Not legal tender (<i>only Bitcoin was legal tender in El Salvador</i>). - Cryptos operate without the support of a lender of last resort.	- Use algorithmic issuance, based on predetermined rules, encoded in their protocols. - Employ decentralised governance mechanisms.	Cryptocurrencies, such as Bitcoin, may derive their value from network effects and market dynamics.	The exchange rates are unpegged, leading to ample volatility of prices, even intraday.	- The blockchain offers permanent settlement finality when transactions are confirmed. - The absence of an issuer eliminates counterparty risk but leaves the asset vulnerable to market fluctuations that can cause rapid value loss. - Settlement involves a currency not backed by fiat money, generating currency risk.	- Cryptos are used within crypto-native asset trading. - They are generally not used to settle securities tokens due to their instability as a settlement medium, alongside regulatory concerns.
Stablecoins	- Not legal tender. - Stablecoins operate through private issuers who maintain a claim against a company, and they are frequently established as claims on reserve assets.	- Claim against reserves of fiat currency and other assets. - Alternatively issued through algorithmic mechanisms. Typically governed by private companies, subject to accountability, systemic and other risks.	- Fiat-backed stablecoins maintain reserves of traditional assets, although the quality and transparency of reserves may vary. - Algorithmic stablecoins, like DAI, maintain peg through over-collateralised crypto loans.	Stablecoins maintain a peg to fiat currency but may experience deviations from par value when market stress occurs.	- The network achieves on-chain finality but remains incomplete, according to central bank standards, until final redemption. It exposes investors to both counterparty risk from the issuer and potential quality issues of the reserves held. - The stability of a stablecoin depends on the quality of its reserves because it lacks the lender of last resort support.	- DeFi platforms use stablecoins as a currency alternative. Without CBDCs, tokenised asset platforms process settlements through stablecoins but regulators express concerns about potential risks. - This approach can function as an interim solution. Future applications could face tighter rules.

Asset	Legal Nature	Issuance mechanisms	Backing Assets	Value Stability	Settlement Finality and Risks	Market scenarios
Tokenised Deposits	- Not legal tender. - Regulated under banking laws or other regulatory frameworks.	- Deposit claim issued by commercial banks, as digital representations of traditional deposit liabilities. - Governed by commercial banks, under existing banking regulation.	Tokenised deposits are backed by the same assets and deposit insurance schemes that protect traditional bank deposits.	A hybrid instrument that allows traditional bank deposits to exist as digital tokens on blockchain networks, while maintaining legal protections, improving efficiency through programmability	- Final settlement for tokenised deposits happens when they are exchanged for central bank money through bank redemption. - Until redemption, investors hold a private liability, which may be insured under a Depositors' compensation scheme. - Payment's finality exists solely in the ledger, which does not offer the legal finality provided by central bank settlements.	DvP and PvP settlements, within commercial use cases.
CBDCs	Legal tender. Wholesale and Retail CBDCs function as central bank liability and serve as legal tender.	- Central bank money issued by national monetary authorities. - Governed by central banks within existing monetary policy frameworks.	CBDCs are backed by the full faith and credit of the issuing government.	Pegged to fiat (identical to national currency unit).	- The asset value is fixed to the national currency unit. - The settlement process uses central bank money, eliminating counterparty risks. - Decreases settlement periods for securities, derivative margin payments, cross-border trade finance payments.	- DvP and PvP settlements though CBDCs provide an ideal mechanism for risk-free settlement of tokenised assets. - Central banks provide intraday credit, minimising potential liquidity and credit risks.

Source: Author's elaboration.

4.3.1. UNDERLYING PRINCIPLES, ADVANTAGES, AND SETBACKS

The stability of the settlement process for securities, and a range of assets, depends on the reliability of the settlement asset representing the money side of the transaction. Traditional market operations require cash settlements to be finalised through central bank money, such as reserve transfers. The settlement process involves transferring central bank reserves, thus removing the credit risk between the parties involved. A secure digital settlement option for tokenised asset marketplaces is embodied by CBDC, which hold fundamental importance for tokenised settlements, and may be able to unleash multiple advantages. Firstly, according to Carstens (2022), the sovereign backing of CBDCs may reduce credit risk between parties, while maintaining the unit of account. The early tokenisation experiments demonstrated that central bank money is essential to achieve a successful outcome of transactions, as stablecoins need to acquire credibility through external means and face the risk of losing their parity function (Garratt and Shin, 2023). Central banks establish the economy's unit of account, while ensuring monetary stability (BIS and CPMI, 2024). The settlement of trades in central bank money creates trustworthiness in payment value among parties, while maintaining money unity and ensuring, for example, that one euro retains consistent value across different forms, safeguarding the singleness of money (BIS and CPMI, 2024). Settlements conducted through private tokens may introduce extra credit risks and deviations from the par value. The BIS has underlined that tokenised payment systems may connect to central bank money, to prevent the monetary system fragmentation. Failures of various crypto-assets and stablecoins demonstrated the irreplaceable nature of central bank money as trustable currency. According to Ahmed, Aldasoro and Duley (2024), stablecoins attempt to replicate central bank money but cannot ensure its inherent safety, while crypto markets remain self-reliant, with minimal interactions with real assets, rendering them inadequate for future financial systems. Integrating CBDC into tokenised asset platforms may seamlessly connect new digital markets to the established financial system, while preserving foundational trust in money.

When a tokenised asset trade is settled with CBDC funds, the seller holds an irreversible payment from the central bank, which eliminates the need for any additional reconciliation or clearing procedures. DLT systems may enable instant settlement finality, similarly to cash transactions in RTGS systems. Atomic DvP capabilities through CBDCs ensure that both transaction legs settle together or fail together, avoiding situations where the asset delivery occurs without the payment, due to intermediary defaults, delays, technical or operational issues. Experiments conducted by the BIS, the Swiss and French central banks demonstrated that DvP using wholesale CBDC systems is technically feasible, and it may improve post-trade

procedures over conventional methods (BdF, BIS and SNB, 2021). Participants to pilot projects achieved faster settlement and improved transparency, by using a common DLT platform to handle multiple currencies, to conduct real-time direct transactions beyond the limits of traditional correspondent banking arrangements. The use of CBDC settlement eliminates multiple intermediaries and might reduce time delays in the settlement process for tokenised assets, resulting in lower operational risks and better liquidity management, while enhancing process efficiency.

Settling transactions in central bank money removes the necessity for parties to evaluate the settlement medium's liquidity and creditworthiness. Settling stock trades with commercial bank money in traditional markets presents a small risk of bank failure, before the settlement of obligations, while confirming the integrity and the compliance of the payment. As CBDC represents an obligation of the central bank, it virtually carries no credit risk. In tokenised systems, users who receive payments via stablecoins or e-money tokens, face issuer's credit risk until they convert the tokens into central bank money. CBDC users may access central bank credit facilities, including intraday liquidity, that private token systems lack. Wholesale CBDC systems may benefit from intraday credit facilities (similarly to current RTGS systems), taking advantage of elasticity measures to complete large transactions (Garratt and Shin, 2023). Central banks usually offer banks intraday credit, backed by collateral, to support the processing of payments. A CBDC settlement network could provide similar credit facilities to ensure the smooth completion of large transactions, which stablecoin issuers and crypto platforms currently do not provide. Most stablecoin issuers fail to provide credit facilities, which potentially impedes settlement efficiency, by affecting speed and cost, since stablecoin users cannot access short-term liquidity solutions (Ahmed, Aldasoro and Duley, 2024). In comparison to other systems, a CBDC system established within a central bank can embed liquidity saving features and lender of last resort safeguards, which maintain continuous settlement operations during stressful situations, in a similar setup of existing RTGS systems.

The legal finality of central bank money settlements is firmly established, while stablecoin and crypto payment enforceability varies based on the issuer's jurisdiction and bankruptcy laws. Central banks and governments may establish transparent legal frameworks for the operation of CBDCs. This may guarantee settlement finality for central bank payments, while also providing clear guidelines for dispute resolution and default management. To achieve widespread participation, tokenised asset markets require the same level of legal clarity established for other financial systems. When a tokenised bond trade settles through CBDC, the payment leg becomes final and receives the same legal protection as traditional central bank transactions. Regulatory authorities alongside central banks have shown apprehension

towards the use of unregulated tokens for major financial transactions. The application of CBDCs for settlement purposes may bring tokenised markets into compliance with existing regulatory frameworks. CBDCs represent a more direct solution for digital asset settlement, as it places transactions under established legal protections, instead of adding protections to private coins. The seamless connection between CBDCs and central bank deposits removes ambiguity, enabling financial institutions to engage more confidently in tokenised marketplaces.

The availability of CBDCs in tokenised marketplaces enables the development of new technological innovations. Developers can program atomic multi-party transactions (e.g. an automated repo platform, driven by smart contracts, might enable a seamless exchange between bond tokens and CBDCs with precise interest calculations, while ensuring payment execution finality). Smart contracts can utilise CBDC to execute payments, according to complex conditional logic, when predefined conditions are met, for instance, due to asset delivery or external events confirmed through predefined oracles. This may create new trading mechanisms and financial instruments. The integration of CBDC with smart contract logic enables conditional escrow capabilities and automated repo operations, while maintaining monetary integrity alongside composable multi-leg trading functions. The benefit of CBDC lies in its ability to support these innovations, without generating convertibility or credit risks. The BIS (2022a) argued that combining central bank money with assets on a unified platform may allow transaction bundling and process automation, beyond current practical capabilities. The technology can advance current securities settlement methods, while enabling the creation of novel market frameworks, such as peer-to-peer tokenised security trading with immediate cash margining, and automated escrow solutions for trade finance. Participants currently face inefficiencies, due to the use of prefunded fiat escrow systems or to less reliable tokens for money transactions. CBDC may serve as a powerful driver for unlocking tokenisation's capabilities, by integrating DLT with the secure framework of central bank money. Pilot project data provides empirical support for these claims. Research from the BIS (2023h) demonstrated that wholesale CBDCs in tokenised exchanges simplify settlement processes and decrease associated risks. Regarding the Banque de France experiments, strong industry demand emerged for central bank money tokens to settle digital assets to enhance safety and trust (BdF, 2024b). Central bank digital currencies may become essential for achieving the tokenisation's potential in mainstream finance because they offer the stability which central bank money has delivered through conventional financial systems.

Academic researchers have adopted different viewpoints regarding the tokenisation's potential for transformation, due to different regulatory frameworks, unresolved technical challenges

and varying institutional factors. According to Cisar et al. (2025) and Roosz (2024), tokenisation might reduce current costs, while making capital markets accessible to more participants. Pilot projects on bond and repo trading provide support to this theory, however, scalability issues continue to persist on public blockchain networks (Bulgakov et al., 2024). Benefits observed include quicker settlement time, reduced to hours or near-instant from the days required by the conventional process. Additional advantages are expected by the reduced clearing and reconciliation costs, together with an expanded access to illiquid asset classes, such as real estate. Advocates believe that CBDCs may serve as key enablers of the tokenisation, by providing government-backed settlement systems that reduce the credit risks of private digital currencies (BIS, SNB and SDX, 2020). A successful launch of CBDCs in major economies could lead to widespread acceptance of tokenised markets, through the provision of universally trustworthy on-chain liquidity. Researchers address the challenges surrounding the scalability and the legal enforceability (OECD, 2020). As evidenced by the Iuliano and Di Nucci (2024), advancements in smart contracts efficiency might be defied by new vulnerabilities, introduced by code risk and governance challenges, along with potential liquidity shortages. Progresses in the Decentralised Finance (DeFi) demonstrate empirical risks, while permissioned DLT pilot programs may reveal effective mitigation strategies. Authors argue that existing blockchain consensus mechanisms may become overloaded by high-volume markets, generated by the migration of major equity exchanges to tokenised markets, resulting in a congestion of transactions and in a potentially unacceptable latency for the processing turnaround time (Casey et al., 2018). Besides, researchers highlight that numerous jurisdictions do not have complete regulatory definitions for tokenised assets, this may create uncertainty regarding the legal agreements and the potential court decisions for smart contract disputes or unauthorised transfer claims (Park, Lee and Kim, 2024). A balanced stance emphasises the crucial need for effective policy frameworks. According to the OECD (2020), the effectiveness of tokenisation relies on the creation by authorities of standardised and interoperable regulations for digital assets. The researchers suggests that beneficial outcomes may depend on cohesive regulations and adequate prudential capital standards. The MiCA (European Parliament, 2023) and the Basel d545 (BCBS, 2022) regulations promote regulatory convergence, however cross border fragmentation may persist. Current limitations in interoperability standards and the absence of a clear guidance could cause tokenised solutions to operate in isolation, restricting their potential to deliver the expected benefits.

While tokenisation offers strong theoretical benefits, it faces variable practical implementation. The fractionalisation enables increased liquidity for assets, such as fine art holdings and private equity shares, as these asset classes suffer from illiquidity, beside high transaction fees. The increase in market liquidity is a main benefit often recognised for real estate

investments, affected by restricted groups of potential investors, due to their size. The asset fractionalisation enables retail investors to acquire fractional pieces of expensive assets such as commercial real estate, broadening the access to markets. Tokenising ownership into smaller units reduces entry requirements for investments which should theoretically draw a broader investor audience, even to potentially illiquid asset classes, such as real estate (Kreppmeier et al., 2023). The borderless nature of DLT infrastructure permits issuers to access investors worldwide, while remaining compliant with regulations. The creation of secondary market liquidity requires both market depth and adequate trading volumes, alongside the presence of market makers and investor trust, which the tokenisation process alone cannot inherently provide. A streamlined and automated settlement, through smart contracts, may minimise transactional expenses throughout the entire value chain, decreasing the dependence on some intermediary functions, currently essential for clearing, settlement, and asset servicing. A unified ledger system may remove the necessity for parties to maintain separate records and to continuously reconcile them. Cisar et al. (2025) indicated that settlement processes could reach the T+0 days target and decrease counterparty risk exposure, potentially reducing capital adequacy obligations for financial organisations. The evidence for efficiency improvements is observed in case studies, pilot programs and limited commercial deployments. The Swiss SDX platform has demonstrated that real-time settlement (T+0) is achievable in equity markets. The EIB (2022) showcased the benefits of blockchain based settlement, when they issued tokenised bonds, enabling the reduction of the transaction completion time from T+2 to T+0 or 0.5 hours. The ability for parties to complete transactions instantly helps lower settlement and counterparty risks, according to the BIS (2023h). The OECD (2020) reports that automating the dividend payments, combined with computerised coupons' distribution and streamlined corporate actions processes, may decrease the need for manual processing tasks, unlocking substantial savings. Research projects and pilot tests carried out by organisations like Euroclear and DTCC, aimed to discipline the operating procedures (DTCC et al., 2024). Every authorised participant may have access to an identical set of transaction records, hence improving the auditability, with the automated production of audit trails, whose transparency level varies between public and permissioned ledger systems. Regulators may gain direct access to market data, to support their supervisory activities and the performance of risk assessments. Cryptographic hashing features may protect historical records against tampering, thus strengthening the data integrity. Smart contract tokens may integrate automated regulatory compliance features, for example, to restrict transfers initiated by ineligible investors. The companies' shareholders may be tracked and updated automatically through the system. Financial products, such as derivatives or structured products, may be originated to trigger automatic payouts, when specific events occur, or when relevant data is received through preset oracles. The WEF's

modelling indicates that improvements in the collateral mobility could release over USD100 billion of top-tier collateral, though the adoption of on-chain rehypothecation practices (WEF, 2025).

Although evidence shows positive results, achieving full efficiency improvements may require strong interoperability standards alongside regulatory support. The broad implementation of tokenisation faces substantial challenges that may prevent its expansion, and key unresolved barriers remain. Financial institutions must implement substantial modifications to their internal compliance operations and to their document management systems, when adopting blockchain technology on a large scale (OECD, 2020). The strength of network benefits, which increase with growing participant numbers, may be at risk as early tokenisation projects used multiple incompatible blockchains (Casey et al., 2018). The global issuance and trading processes face complexities, due to diverse national regulatory frameworks, for example, various jurisdictions such as the UK, Singapore, and Switzerland utilise different regulatory principles, to supervise DLT application testing. Classification systems for numerous tokens remain inconsistent across different regions. Ensuring investor protection in DLT environments collides with the complexity of providing sufficient disclosure, appropriate suitability standards and recourse mechanisms. The definition of legal terms, to specify when a blockchain transaction achieves the irrevocable settlement status, is necessary to confirm the settlement finality.

The transaction processing capacity of current DLT platforms falls short of processing major financial market volumes, without encountering delays or excessive costs, unless throughput limits will be improved. Maintaining scalability and security, while keeping decentralisation has proven to be a challenge. According to Lehmann (2025), new methods are in development and require further maturation, for instance, the L2 method, which includes improved consensus mechanisms and rollups, is supposed to enhance the efficiency, by performing computational work of layer 1 (L1) of the blockchain in secondary network. The technological landscape includes multiple DLT systems that face challenges in communicating and transacting with other platforms. The absence of standardised technical frameworks and data lineage prevents the smooth integration across systems. International organisations are developing unified APIs and ISO standards, to counteract the market divisions, caused by different technologies. The fragmentation of liquidity pools over several incompatible ledgers may generate substantial risks (BIS and CPMI, 2024). However, cross-chain bridges and interoperability protocols may introduce new operational risks alongside security threats (Ping, 2024; Swift, 2022). The banking sector may benefit from the adoption of wCBDCs, but the expansion of tokenised markets requires the adoption of efficient digital cash solution. Until

when CBDCs may reach a production-ready state, the gap may be bridged by regulated stablecoins or by tokenised commercial bank money (Garraat and Shin, 2023). The ability to seamlessly exchange CBDCs with tokenised assets may transform the bank reserve management, and the monetary policy targets, while policymakers examine protective measures, such as CBDC holding limit and transaction caps to decrease potential disintermediation risks (BIS and CPMI, 2024). DLT systems may provide security advantages but may introduce new risks. Exploitable vulnerabilities of smart contracts might transform into failures, as exemplified by the DAO hack (Mehar et al., 2017). Although detailed audits remain crucial, they cannot guarantee the required security. Protecting the assets' private keys from unauthorised access remains the most critical security measure. Key holders face frequent phishing and social engineering attacks. The disappearance or theft of private keys leads to the permanent loss of linked digital assets. Proof-of-work public chains face the risks that a single entity might control most hashing power and might manipulate network transactions. Permissioned ledgers face potential risks from their network governance structure, which can lead to collusion and unfair alterations to rules.

Systemic risks remain a possibility, due to faster transaction speed and more complex programmable assets, which could both quicken market disruptions and hide fundamental dangers. Market activity may become dependent on a limited number of dominant DLT platforms, or service providers, which could lead to new single points of failure. Widespread stablecoins should be treated as systemically important payment systems, which may result in a regulatory framework that diminishes their economic benefits (Ahmed, Aldasoro and Duley, 2024). Finding the right equilibrium between regulatory compliance and user privacy continues to be a design challenge. wCBDCs may expose transactional data to central banks, while rCBDC may protect end-user data through accounts serviced and controlled by intermediaries. Research into zero-knowledge proof methods continues to advance to reduce specific risks (Azimi et al., 2025). DLT systems need to establish robust defence mechanisms to withstand system failures and software defects along with cyber threats. Change management procedures may ensure the update of DLT protocols and smart contracts, while maintaining uninterrupted operations. The applications must follow established protocols for addressing errors and disputes that arise from automated processes that might malfunction or generate unexpected results. Assigned systems' responsibilities must be clearly defined for platform operators, validators, and developers to prevent the occurrence of failures or losses. The potential risks which require policy and technical solutions for mitigation, are summarised in the following table.

TABLE 17: CRITICAL FACTORS, KEY FINDINGS AND SOLUTIONS FOR TOKENISED ASSETS

Critical Factors	Key findings	Potential solutions
Scalability and throughput	• Crypto asset platforms can settle few transactions per second (for instance, Ethereum demonstrated settlement of approximately 15-30 transactions per second in L1 and 24k+ in L2) which is insufficient for handling peak equity trade volumes.	• The adoption of solutions such as network layer 2 solutions (bundling transactions off-chain and submitting proofs to L1); permissioned Byzantine fault-tolerant systems; and off-chain trading mechanisms, can help in improving the settlement capacity of the platforms.
Smart-contract vulnerabilities	• Coding flaws are responsible for exploited failures and operational issues.	• Audits from third parties along with formal verification methods may detect and assess hidden vulnerabilities.
Governance and legal enforceability	• Enforceability of legislation requires clarifications on the applicability of legal frameworks for specific services.	• International legal frameworks may offer guidance to providers in terms of applicable rules for specific services.
Key custody and cyber-risk	• The mismanagement of private keys may result in title loss, which represent infrastructure risks.	• Multi-Party Computation (MPC) combined with Hardware Security Module (HSM) protection may represent valid technological solutions.
Regulatory fragmentation	• Cross-border transactions may face delays, due to regulatory fragmentation as only few banks can trade tokenised securities across jurisdictions.	• The use of international common standards may reduce the fragmentation and foster interoperability.

Source: Author's elaboration.

4.3.2. TECHNICAL PROTOCOLS AND INTEROPERABILITY SCENARIOS FOR CBDCs

Technical protocols and transaction workflows require common design to enable interoperability between CBDC systems and tokenised asset platforms. Atomic settlement requires the concurrent transfer of asset tokens with payment, or the process fails entirely. Across tested solutions, several models have emerged to enable the technical integration. A direct method to integrate CBDC systems with tokenised asset platforms involves placing both asset tokens and CBDCs on single or interoperable DLT networks. This design foster integration, by maintaining both the tokenised asset and money in one or interoperable platforms that execute exchanges through transfer mechanisms. Smart contracts may enable

the exchange between tokens. Transactions can achieve finality, with minimal friction, when central bank digital money and other tokenised claims share a common ledger system. According to the BIS and CPMI (2024), the full tokenisation benefits, such as automation and programmability, become achievable when settlement finality derives from central bank money, coexisting with other claims in a unified system, and enhancing trust through central bank authority. A practical application may involve issuing wholesale CBDCs on a blockchain that also process securities' issuance, as demonstrated by Project Helvetia on the SDX platform (BIS, 2022a), or by creating a collaborative platform managed by central banks and private entities that could manage both tokenised assets and digital cash tokens. A high-level design of these applications may foresee a unified ledger that maintains separate partitions for central bank money, private tokenised money (i.e. bank deposit tokens), and tokenised assets which operate under the same rules, interacting via smart contracts in the same execution environment (BIS, 2023h).

A second option may require the use of technical bridges or integration layers to enable exchanges between CBDCs and tokenised assets. The implementation of Application Programming Interfaces (APIs) to connect systems may allow tokenised platforms to debit digital money from users and to credit sellers with token transfers, interfacing two or more systems, instead of achieving atomicity on a single blockchain ledger. The development of interoperability standards is currently ongoing to enable different DLT networks to exchange payments and digital assets. The atomic DvP settlement between assets and CBDCs requires systems' integration, when they are located on separate platforms and ledgers. Different ledgers may enable atomic swaps through Hashed Time-Lock Contracts (HTLC) (BdI, 2022) or trusted interledger protocols (Interledger Foundation, 2025), while the Regulated Liability Network (2022) aims to link central bank and commercial bank tokens with e-money tokens on a unified network. Cryptographic protocols, such as HTLC, enable the synchronisation of asset transfers between different networks. The HTLC mechanism locks the asset token on its source ledger, while the payment remains locked on the cash or CBDC ledger, until both parties confirm each other's lock with cryptographic proofs, to release or trigger a refund call, after a timeout period. The Banque de France demonstrated how their CBDC prototype platform (DL3S) connected with J.P. Morgan's Onyx network, through HTLCs, to establish cross-platform DvP and to secure fund transfers between the systems (BdF, 2024b). This pilot project marked one of EU first recorded instances of interoperability of bank deposits in tokenised form and CBDCs. The Banque de France collaborated with the Innovation and Development centre of the Italian Banking Association (ABI Lab) and several other entities to settle interbank balances via a DLT platform (LEONIDAS - Liquidazione Efficace ONchain DLT Asset su Spunta) through their central bank ledger interface, using timed lock and unlock

procedures (ABI Lab, 2024). This project demonstrated that atomic settlement across different ledgers is possible through cryptographic coordination (BdF, 2024b). Banca d'Italia introduced a new protocol called TIPS Hash-Link which functions as an API based solution that works independently of specific DLT platforms and supports flexible connections, between market infrastructure systems and multiple DLTs. The TIPS Hash-Link evolved from the HTLC, adding specific enhancements to address common failure scenarios, while using a clone of the TIPS system as a platform for managing DvP transactions securely, through DLT systems (BdI, 2022).

Instead of using HTLCs, traditional interoperability solutions rely on trusted intermediaries or messaging platforms to manage operations across multiple systems. A third way of ensuring interoperability is through trigger mechanisms, which can establish conditions on exchange platforms (e.g. a smart contract event on a DLT system) to automatically prompt a payment action in other systems, this could be compared to an API call to initiate a central bank RTGS fund transfer. In this way, a smart contract event, occurring on a distributed ledger system, can initiate automatic payment actions in another system, through predefined rules. A central bank RTGS system can receive instructions to transfer funds through an API call (ECB, 2023c). The ECB plans to enable the interoperability for DLT settlements through trigger systems (ECB, 2025). In the medium term, through an interface with TARGET services, DLT platforms could enable tokenised trade executions to trigger an API call that transfers the corresponding funds in the traditional system, completing the settlement in central bank money. The two separate ledgers would continue to operate independently, but they would synchronise instantaneously on the DLT platform and on the RTGS system.

A fourth different approach was identified by Swift, the global financial consortium, which prototyped an interlink solution in its CBDC sandbox. Swift evaluated network of networks connectors to enable the conversion of ISO20022 messages across various CBDC platforms and tokenisation systems, achieving the execution of atomic DvP transactions, involving several central banks and commercial banks (SWIFT, 2024). This interlinks solution simulated the connection of CBDC networks, built on various technologies, with a tokenised asset trading platform, using automated message triggers and escrow accounts for the orchestration of DvP transactions. The Swift experiment demonstrated that existing CBDC networks can connect with a tokenisation platform across multiple technology stacks, through straight-through processing across separate networks (SWIFT, 2024). The atomic DvP orchestration was achieved by automatically synchronising the payment leg and the asset delivery. The asset transfer milestones triggered payment events, which were confirmed through standard messages, to guarantee the simultaneous settlement of both legs. Technical standards

development for digital assets and interface applications to CBDCs represent key complementary aspects. Different systems can interpret transactions similarly through consistent data and messaging standards, such as ISO20022 or newly developed token standards. Connector nodes or gateways enable the conversion of token platform instructions into RTGS payments or Instant Payment Systems and vice versa. The BIS Innovation Hub implemented projects such as Project Meridian to investigate the application of APIs for payment initiation for tokenised asset platforms (BIS, 2023a). Through Project Meridian FX, the BIS Innovation Hub evaluated how gateways can perform payments for tokenised assets, while exploring the role of RTGS, in delivering conditional settlement to DLT systems (BIS, 2025). The development of interoperability standards that include identity frameworks and transaction formats is essential for scaling cross-platform solutions. Both central banks and industry organisations, such as ISO and SWIFT, participate in setting standards for these projects and are actively working to establish rules that could allow tokenised assets created in one network to be seamlessly recognised and settled with funds held in another network.

Multiple technical protocols and interoperability scenarios may coexist for an extended period. Every technical method exhibits both positive attributes and negative drawbacks. The single unified ledger approach delivers high efficiency and programmability, since all data would reside in one location, however it presents governance and scaling issues, as a single ledger, i.e. a single point of failure, cannot realistically process all market transactions at once. Practical methods foresee the implementation of application interfaces across platforms, while maintaining independent systems, however, this scenario may introduce complication and the fragmentation of liquidity pools. These bridging approaches create dependencies on intermediary systems, while also facing the risk of failure for individual components. The BIS and SWIFT introduced models where different ledgers, designed for specific use cases, connect through APIs, to maintain interoperability in a network of networks system (BIS, 2025; SWIFT, 2024). Current initiatives focus on linking existing systems such as the Swift connector, as a practical intermediate measure, while striving toward the goal of fully integrated platforms (SWIFT, 2024). The development of integrated domestic capital markets ledgers, alongside multi-currency cross-border CBDC networks continues to progress simultaneously (BIS and CPMI, 2024; ECB, 2025). Technical pilot projects with HTLC atomic swaps and API triggers can create versatile interoperability instruments, tailored to specific applications such as domestic DvP and international Pvp. The wCBDC platform from the Banque de France has demonstrated DvP settlement of tokenised securities, reporting strong market participant interest in using central bank money for tokenised markets over DLT (BdF, 2024a). Although technical frameworks exist to integrate CBDCs with tokenised assets, obstacles remain for the standardisation of protocols and the scalability of these technologies.

4.4. CONCLUSIONS FOR THE ASSET TOKENISATION PROCESS AND ITS SETTLEMENT IMPLICATIONS FOR CBDCs

The asset tokenisation process marks a major advancement in financial systems. By combining traditional financial practices with DLT technology and smart contract functionalities, it delivers an effective strategy to modernise conventional financial markets, and this approach presents proven benefits in reducing the turnaround time of settlements, in decreasing expenditures and in widening investor accessibility, according to Cisar et al. (2025) and to Rooz (2024). Financial markets are undergoing a gradual integration of tokenisation products, sustained by the growth of related support services. Bond and fund markets along with collateral markets are implementing tokenisation practices beyond experimental stages into actual operational use. This scenario could be further developed by the introduction of CBDCs, as they might accelerate the adoption rate by delivering both legal and reliable digital payment methods, reducing existing counterparty, credit and liquidity risks in tokenised transactions (BIS, 2023h). Specifically, the emerging wholesale CBDCs may establish the secure settlement layer that was previously missing, while ancillary service providers may deliver custody solutions at institutional level, along with compliance and audit services. In fact, the ecosystem may benefit from several support services, including private key custody, compliance analytics, smart contract auditing, and risk management assessments which may help to overcome the technological and regulatory challenges of decentralised digital assets (BIS and CPMI, 2024; OECD, 2020).

Uncertainties in the way forward are caused by varying regulatory policies, non-standardised international regulations, unresolved legal enforceability issues, technology limitations in underlying solutions and in technical interoperability among various blockchain networks. (OECD, 2020; WEF 2025). The compromise that stakeholders and policymakers may reach in regulations and governance, may influence the transformation of the tokenisation process, in the global financial sector. Scholars express conflicting opinions with advocates emphasising efficiency gains and financial inclusion benefits, while opponents point out scalability and governance problems, which make implementations more complex than the results from pilot projects may indicate.

This chapter investigated the application of tokenisation, across both public and private blockchain platforms, which can process diverse tangible assets, e.g. real estate, equities, bonds, commodities as well as intellectual property, and collectibles, to be transformed into digital tokens. Ethereum technical standards (ERC-20 and 721) were instrumental for the establishment of basic principles of tokenisation, but new solutions (ERC-1400 series, ERC-

3643 and similar standards on Corda, Hyperledger, Stellar and Tezos) could be used to address compliance issues and to facilitate complex asset structures. Digital tokenisation allows for the rapid conversion of assets into digital forms. This process demands coordinated efforts with the regulatory provisions and existing infrastructures, to preserve connections between digital tokens and their real-world assets. The tokenisation process provides a transformative approach that can simplify existing procedures for all participants.

A shared or interoperable immutable ledgers, along with smart contract automation, may resolve the drawbacks of legacy systems, while enabling transparent asset transfers (WEF, 2025). Initial pilot projects and commercial applications show practical viability and measurable advantages for specific applications including fractionalisation of illiquid assets and bond issuance/servicing operations (Ebadi, 2025; Siemens, 2024). The case studies demonstrated the advancements of the asset tokenisation process, with international institutions issuing tokenised bonds and banks employing tokenised deposits for daily transactions, whereas platforms may enable fractional asset ownership for assets (such as property and art), which previously remained inaccessible to retail investors. While these positive outcomes promise compelling advantages, including quicker issuance processes and wider market access, along with continuous trading possibilities, they also uncover obstacles (such as fragmented liquidity across the platform and regulatory barriers), which reduced the potential benefits initially envisaged. The failures identified so far include unsuccessful token exchanges and regulatory actions against non-compliant offerings. Central bank pilot projects of CBDCs demonstrate the transformation potential of securities and monetary markets, by combining tokenised assets with tokenised currency, to facilitate atomic transactions in central bank money (BISIH et al., 2022).

The future financial system may support the interoperability between CBDCs and tokenised assets, as markets start to adopt digital asset infrastructures. Retail and wholesale CBDCs promise to deliver secure and effective digital cash that seamlessly integrates with tokenised value chains, ranging from interbank bond trading platforms to tokenised securities retail investment applications. Several technological protocols such as unified ledgers and atomic swap bridges, along with API connections, are being developed to support CBDC operations. A range of protocols is currently under testing to achieve seamless DvP and PvP functionalities for CBDCs, within distributed ledger systems. Initial implementations from central banks and consortia including the BIS Innovation Hub projects, ECB and the Banque de France experiments, along with Swift's connector (BdF, 2024b), demonstrated the practical results. Emerging developments are establishing operational expertise and standards to support extensive future adoption.

The rationale for using CBDCs in tokenised asset settlement is compelling, as CBDCs provide transaction finality and remove credit risk, while preserving the monetary unit of account in these new systems, to match the sovereign currency (BIS and CPMI, 2024). Unbacked cryptocurrencies are not ideal to function as settlement assets as price volatility and the absence of a lender of last resort present major concerns (BIS, 2023e). Participants using BTC-denominated cash legs remain vulnerable to currency fluctuations that can erase asset price gains, despite deep blockchain finality. The functionality of stablecoins, such as USDC and USDT, demonstrates the market need for digital fiat currency services, but their inherent credit and regulatory risks position them as temporary development, rather than long-term solution (Garratt and Shin, 2023).

The debate on CBDCs versus stablecoins has practical implications about which entity will establish trust in future digital markets. Current findings indicate that CBDCs represent the essential element to safeguard the settlement processes in tokenised finance, by merging the technological advancements, with reliable monetary system foundations (BIS and CPMI, 2024). The function of stablecoins as temporary solutions reveals the need for digital currency alternatives and exposes their trust and stability issues, according to Ahmed and Aldasoro (2025). As CBDC initiatives advance and regulatory frameworks such as the EU's MiCA apply tighter oversight to stablecoins, settlements of tokenised assets may shift toward central bank electronic money, like wholesale CBDCs, or tokenised bank deposits tied to central bank reserves. CBDCs may operate as the digital adhesive that unites the developing tokenised economy. interoperability may become the enabler of digital asset exchange in fiat money, through unified ledgers or robust bridging protocols that can allow central bank money to become the settlement medium for tokenised assets, similarly to how traditional assets settle today. CBDCs may increase market confidence, lower systemic risk, reducing turnaround time and enabling large-scale efficiency improvements. Despite the absence of launched wholesale CBDCs, actively used by major jurisdictions markets, pilot programs continue to develop quickly, with central banks in Asia (Hong Kong, Singapore), Singapore and the Middle East (UAE, Saudi Arabia), who have conducted successful tests of cross-border CBDC exchanges, showing that multi-currency tokenised platforms may become reality (BIS, 2024). The e-CNY represents China's advanced CBDC deployment, which may potentially integrate with tokenised marketplaces, including local or decentralised exchanges. In the private sector, large financial market infrastructures are preparing for a tokenised future, Euroclear and DTCC have conducted digital bond settlement experiments using digital cash and consortia (DTCC et al., 2023). Together with CBDC initiatives, these projects support the role of central bank money, being represented as cash on a DLT ledger.

Looking forward, a plausible scenario is one in which hybrid models may operate concurrently. According to the ECB (2025), central banks plan to link current RTGS systems with DLT and to create unified ledgers, which may enable tokenised assets, to settle using central bank money, like current traditional securities. Central banks may supply the fundamental settlement currency (either CBDC or reserve-backed tokens), while private entities may lead the development of asset tokenisation and trading platforms. APIs and shared standards may allow systems interoperability, while enabling users to exchange tokenised assets for money, with the same seamlessness, but with increased speed and the reliability of current payment systems. The implementation of this vision mandates extensive collaboration between public and private entities. According to the BIS and CPMI (2024), central banks with their public mandate stand in the best position to offer the neutral settlement layer based on trust, while private sector companies should focus on pioneering innovation and customer-facing solutions.

Regulators globally are actively exploring tokenisation initiatives. While the U.S. enforces the SEC's decision to handle tokenised securities as traditional securities and implemented new legislation, such as the GENIUS act, the industry seeks to develop clearer channels for the involvement of retail participants. The EU has established practical measures, through the MiCA and the DLT Pilot Regime, to promote innovation, within a regulated structure (European Parliament, 2022; 2023). The jurisdictions of Singapore and Switzerland developed adaptable and strict regulatory systems ahead of others, which led to substantial interest and active projects in tokenisation. Sandbox programs and legal reforms are being implemented by the UK, alongside several other nations.

Regulation aims to legitimise tokenisation, by including it within financial regulatory boundaries, while managing potential risks. This process establishes groundwork for scaled and mainstream adoption. The tokenisation process brings efficiency and liquidity advantages, but these advantages depend on both market structure and investor behaviour. The tokenisation does not generate intrinsic value but serves to release value, that was previously constrained by friction, according to the WEF (2025). The full impact remains undetermined by experts. Will the tokenisation process lead to gradual enhancements in specialised areas such as private markets, or will it trigger a complete transformation of the entire financial sector? Future research may focus on longitudinal studies in active tokenised markets to analyse real-time performance data on throughput, the quantification of potential cost savings, and the enhancement of market liquidity, ideally carrying out comparative studies in multiple legal jurisdictions, to understand the effects of different regulatory frameworks and technological infrastructure. Additional research areas may assess the user experience in

retail tokenisation applications or might develop methods to enhance oracle reliability, while creating strategies to connect private and public blockchains.

The digital transformation may support the solution of several interconnected challenges. The fragmented regulatory frameworks across jurisdictions, may create compliance burdens and cross-borders uncertainty (EU Blockchain Observatory & Forum, 2020). The current state of technology remains progressing, as the scalability efforts for mass market and the interoperability between different DLTs and legacy systems continues to evolve (Ping, 2024). The protection of private keys and the assessment of smart contract integrity require ongoing attention and technological advancements (Azimi et al., 2025). A critical viewpoint necessitates the recognition of potential drawbacks that extend past operational difficulties. Financial markets may experience increased volatility and instant propagation of financial stress from the enhanced speed and efficiency, unless proper safeguards and oversight systems are implemented (FSB, 2024b). The administration of these infrastructures requires complex socio-technical solutions to establish rules and fairness, while determining liability responsibilities. The advancement of CBDC initiatives requires deeper assessments of both wholesale and retail models, to understand their impact on tokenised ecosystems. Adopting the technological perspective, research efforts could focus on the evaluation of execution and latency in multi-ledger DvP systems, to verify the scalability of platforms.

Through the regulatory perspective, an analysis of enforceability standards for smart contracts would be valuable to assess the interoperability of cross-border agreements. From a macroprudential perspective, it could be beneficial to assess the liquidity of tokenised repo, simulating several stress test scenarios. As pilot initiatives progress into full-scale production, while legal structures become established in the medium term, it would be possible to observe how CBDCs may prove essential to tokenised financial systems, to deliver innovative solutions, promoting monetary stability and public trust in currency value. The CBDC integration creates settlement efficiency opportunities, supporting financial stability and reducing risks for the banking system (BdF, BIS and SNB, 2021).

The research paper presented considerable findings. The study reviewed the improvements in accessibility, enabled by the asset tokenisation through fractional ownership. This allows smaller investors to participate in markets that were previously inaccessible to them, thereby broadening market participation and increasing overall market liquidity. The research found that using CBDCs as a settlement method for tokenised assets may lead to quicker and more efficient settlement processes. This may reduce reliance on intermediaries and lowers transaction costs, making the financial system more efficient. The study highlighted the

regulatory challenges associated with asset tokenisation. It found that clear and consistent regulatory frameworks may be essential in enabling effective CBDCs and their cross-border interoperability with tokenised assets. The research identified a growing trend among financial institutions, towards exploring and adopting asset tokenisation and CBDCs. Case studies showed that early adopters are already experiencing the benefits of enhanced productivity and faster turnaround time, in the execution of transactions.

This paper investigated the potential integration of tokenised markets technology with traditional financial systems, as key element for the success of the asset tokenisation process. The findings show the importance of the choice of appropriate technological solutions for ensuring a smooth operation of tokenised markets. Tokenised financial assets may streamline current operational processes, enhance liquidity, improve accessibility, and boost operational efficiency. To achieve successful tokenisation, financial systems must develop scalability together with interoperability and cybersecurity, in an integrated manner. Using common standards enables developers to maximize network effects in their systems. However, regulatory and technological issues require appropriate solutions to unleash the full benefit of the new technologies. The tokenisation process requires the harmonisation of regulatory frameworks across jurisdictions, with the implementation of cohesive governance structures and the establishment of ecosystems of supportive services.

The academic literature and industry publications demonstrate the intricate balance between potential benefits and existing challenges of the tokenisation. The way forward to integrate asset tokenisation into traditional financial markets may involve a careful evaluation of the technological developments, with detailed risk assessments and pilot projects, besides a strong partnership among innovators, established financial institutions and regulatory bodies.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This study presented an analysis of CBDCs, their potential benefits, challenges, and implications for financial systems. The salient findings and contributions of each of the three papers, presented in chapters 2, 3 and 4, are here recapitulated. The three papers present theoretical, practical, and policy-related implications. The research explores the intersection of economics technology and finance, by analysing digital currencies and their potential to redefine monetary policy, financial stability, and asset management, while providing insights into economic and financial theoretical frameworks. The suggested policy measures may affect central banks and policymakers, connecting public policy and governance. The conclusions from the three papers may present a strategic guide for the creation of digital currency systems that promote inclusion and efficiency, while ensuring security, and addressing socio-economic integration and cross-border financial transactions. Investigating the ethical and legal implications of CBDCs and digital assets, reveals connections with law and ethics fields. The results illustrate the groundwork for creating legal structures and ethical standards for digital currencies, while tackling privacy protection and compliance requirements. The third paper on the technical standards, security protocols, and interoperability requirements for CBDCs and asset tokenisation relates to the fields of technology and financial markets. The findings offer both challenges and opportunities for researchers and practitioners involved in building digital currency systems that are secure and scalable, while also being convenient for users.

The first paper establishes a theoretical contribution by developing a comprehensive framework, designed to evaluate CBDCs. This research advances novel approaches to model the complexity of CBDCs, by introducing a framework to systematically assess and compare distinctive CBDCs' implementations. The study provides insights into effective policies for contemporary economic challenges and offers recommendations for policymakers and national authorities considering CBDCs' implementation. The framework examines essential design elements, which include CBDC architecture and technical specifications, in addition to their advantages and disadvantages and potential applications in real-world scenarios. The research is undertaken across four crucial dimensions: policy, regulatory and governance framework; design and technological needs; socio-economic and financial system integration; sustainability and inclusion. The analysis investigates the implications of CBDCs on financial stability, while reducing dependence on conventional banking mechanisms. The paper studies the effects of CBDCs, while examining their potential influence on financial systems and central bank operations. The research findings of the first paper examine both legal

accountability and ethical issues, including privacy protections and possible digital currency misuse. The analysis looks at the necessary regulatory and governance frameworks for securing digital currency stability. The paper studies the potential consequences of CBDCs on monetary policy execution and transmission as well as the management of interest rates. The research assesses the ways in which CBDCs might support or limit central banks' ability to implement and execute monetary policy, while maintaining financial stability. The paper examines how CBDCs affect the modernisation of payment systems. The research underscores the potential of CBDCs to transform and improve payment systems, by enhancing efficiency and security. The chapter addresses crucial elements including security measures, alongside scalability options and user experience factors as well as technology requirements, interoperability and programmability considerations. This study reviews the socio-economic integration factors for CBDCs, including distribution models along with adoption and usage patterns and accessibility levels. The research explores the role of CBDCs in facilitating cross-border transactions, reducing transaction costs, and improving the efficiency of international trade. The study delves into CBDCs' sustainability and inclusivity features, including privacy, financial inclusion, environmental impact, and overall sustainability. This paper evaluates CBDCs as an instrument to promote financial inclusion, providing the unbanked and underbanked populations with digital financial services. This research framework enables organisations to identify optimal practices, alongside key lessons learned. The investigation presented in the first paper delivers an assessment of the critical impacts of CBDCs. The comprehensive analysis of the policy, regulatory and governance structures of CBDC fills a gap in the existing literature, by providing a holistic framework for understanding and designing the necessary foundations for successful CBDC implementation. The chapter provides an extensive analysis of policy and regulatory requirements, for central banks and policymakers, to adopt CBDCs. The first paper addresses ethical and legal considerations, which are not commonly covered in other reviewed research studies. Furthermore, the study provides tangible recommendations for policy development and further research areas, through an assessment of regulatory approaches, design choices and technological impacts on financial systems. Researchers can gain insights to understand the broad implications of CBDCs on financial systems.

The comprehensive framework developed in the initial paper serves as a basis in the second paper for comparing primary retail CBDCs. The second paper examines policy considerations and technological requirements, while exploring implementation choices, alongside institutional collaborations for three different CBDCs. The CBDCs investigated are the Sand Dollar issued by the Central Bank of Bahamas, the eNaira released by the Central Bank of Nigeria and the e-CNY developed by the PBoC. The study contributes to knowledge, by

exploring the CBDCs' integration into three financial systems. The second paper presents structured assessments to deliver objective evaluations of CBDC implementations across the three major projects. The comparative study of the three CBDCs reveals valuable information, about their respective strategies and outcomes. The research examines policy considerations and technological requirements, along with implementation choices and institutional collaboration concerning the three CBDCs. The second study investigates how CBDCs can facilitate cross-border transactions, reduce costs and enhance international trade. The paper evaluates the implications of CBDCs for domestic and remittance transactions, while discussing additional CBDC features for broader application scenarios. Understanding how CBDCs can support financial inclusion, by connecting unbanked and underbanked individuals with digital financial services, is essential to comprehend the technology's social implications. The second paper investigates socio-economic and environmental factors that influence CBDC usage, while examining elements such as accessibility, alongside financial inclusion which remain less explored in other studies on the subject. The document evaluates user experience factors along with tiered privacy and socio-economic influences, to expand the complex understanding of what determines CBDC adoption and usage. Privacy concerns and regulatory compliance represent important concerns that require thorough evaluation. Addressing privacy issues and ensuring regulatory compliance may increase trust and confidence. This study examines the possible geopolitical consequences that may arise from implementing CBDCs. This research stands apart, by taking a comparative stance and examining three primary CBDC projects, through systematic analysis. The second paper examines CBDCs' design and implementation, alongside their impacts, through a detailed comparative analysis of three specific countries. Through a comparative study, using a common framework, the paper delivers valuable insights into different CBDC project approaches and their implications. The assessment offers insights into best practices and lessons learned for future CBDC deployments, while highlighting future improvement opportunities. In-depth analysis of CBDC projects across different nations remains scarce, this study improves knowledge, by examining how national factors, along with design choices and implementation approaches, may affect the CBDCs' operations.

The third paper investigates the potential integration of CBDCs with asset tokenisation methods for real-world assets and other financial instruments. The study delivers a theoretical contribution, by examining how asset tokenisation functions and how it may be integrated with CBDCs, discussing the strengths and weaknesses of this innovative approach, and clarifying the technological and operational aspects of the tokenisation process. Asset tokenisation involves transforming conventional assets into digital tokens, converting ownership of assets like real estate or securities into digital tokens, that are stored and transferred through

blockchain technology. This study reviews the possible impact of asset tokenisation within the financial sector, along with its future development potential. The research explores how CBDCs function as a method for settling tokenised digital assets. The research studies both positive outcomes and drawbacks of this innovation, its impacts on market efficiency as well as on liquidity and transparency. The research includes practical examples of both tokenised implementations and CBDCs' issuance. Tokenised assets may be traded and settled using CBDCs, as the underlying currency or medium of exchange. This research investigates the technical standards and infrastructure for issuing and managing tokens, while exploring regulatory frameworks and analysing platform interoperability among different nations, providing a comprehensive understanding of the end-to-end process. The research outlines both the advantages of asset tokenisation, including swifter settlements and liquidity enhancement, while also examining its potential drawbacks. The study analyses the digital assets' settlement processes, across CBDCs, tokenised deposits, stablecoins and cryptocurrencies. The third paper presents findings through an analysis of emerging financial products and services, based on tokenised assets, which encompass both innovative investment options, and decentralised financial applications. The study assesses how tokenised assets have led to the creation of new financial products and services, exploring innovative investment opportunities, such as decentralised finance (DeFi) applications and other more flexible financial instruments, made possible by asset tokenisation. The findings in this study evaluate case studies that highlight the real-world impact of asset tokenisation and reveal how financial markets have evolved, demonstrating potential applications of CBDCs. This paper uncovers how combining CBDC with asset tokenisation may provide insights into the financial market evolution and establish new applications for CBDCs. The third paper bridges a gap in research on how CBDCs can facilitate the integration of digital assets into the financial system. Investigating the CBDCs' application in asset tokenisation reveals valuable insights into potential uses and impacts for investors, illustrating the viability of CBDCs. The study identifies opportunities for future research development in the field, related to the application of tokenisation to new asset classes and its potential integration with CBDC, which remain limited and continue to generate academic debate.

The overall research presents multiple recommendations for practitioners and policymakers. The three studies recognise the influence of the regulatory environment on CBDCs. The development of robust regulatory frameworks and governance systems is necessary for the stability and security of digital currencies. The papers deliver detailed insights into the policy structures and regulatory conditions, essential for implementing CBDC systems successfully. Central banks should develop legal frameworks and governance policies for CBDCs that include guidelines for the issuance, management, and oversight of operations. This is meant

to protect and stabilise CBDCs' operations. Central banks and international organisations should focus on establishing interoperability protocols and compatibility standards, to support cross-border transactions and to facilitate the integration with financial systems. Policies may aim to develop more flexible frameworks, to support financial inclusion programs, enabling all members of a population, including the unbanked and underbanked individuals, to use CBDC digital wallets, narrowing down socio-economic inequality. Ethical issues should be considered, in combination with existing data protection and privacy rules, to enhance users' trust. Central banks should explore opportunities to collaborate with technology firms to develop technical solutions that meet regulatory standards and to build CBDCs' systems, which may combine advanced technological capabilities with easy-to-use interfaces, aiming to increase adoption and usage rates. Technology companies may specialise in the creation of secure scalable solutions, delivering high reliability and efficiency, and offering user-friendly interfaces and seamless experiences for users. Stakeholder management requires transparency, accountability and careful consideration of end-user necessities. The public should be made aware of the benefits and risks of CBDCs and may be included in the discussions on policymaking, related to digital currencies. End-users should advocate for policies that promote financial inclusion and protect individual privacy and data security. This approach may establish a system that operates in a fair manner for all participants. The public may be receptive of the opportunities of CBDCs and digital assets and may be wary of their risks and challenges. This help to ensure that both individuals and businesses can benefit from the utilisation of digital currencies. Investments targeted towards the research and development may be instrumental to discover potential innovative applications for CBDCs, besides asset tokenisation and decentralised finance. The integration of emerging technologies may enable CBDCs to remain relevant, in a constantly evolving technological landscape.

The combined findings from the three papers develop, challenge, and refine existing knowledge about CBDCs, by exploring their potential effects on the financial system. The first paper establishes a research framework which advances existing theoretical knowledge through CBDC analysis and comparison. Research into design features, technical strengths and weaknesses as well as potential applications, informs the development of a new theoretical framework for CBDCs. The paper addresses a gap in knowledge, by offering a comprehensive structure for analysis, while delving into important policy and regulatory considerations. The study presented in the second paper develops current knowledge through the examination of CBDCs' impacts across three projects. The findings on how CBDCs can improve the efficiency of monetary policy transmission and reduce the dependence on traditional banking systems provide new insights into the role of digital currencies, in modern

monetary policy. The research provides an in-depth comparative analysis of how CBDCs' design and implementation impact its adoption across the three countries. The research identifies the need for more study, to understand the socio-economic factors that may influence the adoption and utilisation of CBDCs by users. The third paper's examination of asset tokenisation and its integration with CBDCs challenges existing notions on asset management and settlement. The advantages and constraints of asset tokenisation, as outlined in the findings, help to understand the integration of digital assets into financial systems. The third research paper establishes a link between asset tokenisation studies and CBDCs, by expanding knowledge on their combination potential. The research paper investigates a novel field that demands additional exploration, through practical applications and academic studies. This study may serve as a resource for researchers, investigating the complexities and technical solutions, related to the tokenisation of digital assets. Overall, the three papers address significant aspects of CBDCs in ways that fill valuable gaps in the current research.

Informed by the research results, the following policy recommendations may be developed for national monetary authorities, policymakers, technology providers and end users. CBDCs depend on established governance systems, legal and regulatory structures, apt to preserve security and stability. Transparent issuance and distribution criteria and consumer protection guidelines, consistent with existing financial regulations, may help to build supervisory frameworks, with clearly defined responsibilities for participants, financial institutions, technology providers and regulators. Policymakers should also be agile and innovation-friendly, by ensuring regular reviews and adaptation of their frameworks, to accommodate technological advances and financial system developments. With effective management, various risks of CBDCs can be mitigated, such as cybersecurity and operational risks, as well as AML/CFT requirements. Central banks should implement effective risk management practices for CBDCs, to ensure the security and integrity of the digital currencies. Maintaining CBDCs' security involves continuous security audits, together with real-time transaction tracking and established incident response protocols. CBDC operational systems require a high resilience level, to withstand service or system disruptions. Monetary authorities need to establish clear governance, with visible accountability structures to achieve trustworthiness, and need to release comprehensive information about their CBDCs' policies, together with operational details. Regular reporting mechanisms must be established, to show complete transparency about CBDC-related operations, including issuance and utilisation statistics. Central banks may implement auditing and oversight mechanism, to properly manage the operations of digital currencies. The interoperability of CBDCs is key to enable cross-border trade and remittance services. Central banks may partner with international organisations to

establish standardised CBDC protocols and interoperability frameworks, including technical specifications for data formats, transaction protocols, and network security. The creation of uniform standards may increase the cross-border adoption of CBDCs, developing the use of digital currencies also for domestic financial transactions. The interoperability may lower operational expenses, while simplifying payment procedures. Financial institutions may invest in research projects that examine innovative applications for CBDCs. The scope of financial innovation may cover a broad range of products, including asset tokenisation, programmable money and DeFi. By promoting innovative use cases, central banks may evaluate their impact on the financial system and integrate them in the CBDCs' design, addressing associated risks and technical challenges. Experimentation practices may include pilot testing and phased rollouts, that allows central banks to gather data, evaluate performance, and to learn from practical experience. Pilot projects serve as useful platforms for studying technical issues, alongside user activities and market behaviour patterns. These pilot programs enable central banks to develop their CBDCs' technical blueprints as well as to improve regulatory practices, before they proceed to full-scale deployment. Through this strategy organisations can diminish potential risks and uncertainties during CBDCs' implementation.

The development of CBDCs may embed a focus on financial inclusion, during both the design and implementation stages. Central banks should make CBDCs available to every group of the society, including unbanked and underbanked people. Building collaborations and partnerships with existing mobile payment systems enables organisations to reach wider audiences. The development of CBDCs' digital wallets and mobile applications should prioritise the ease-of-use principle and the provision of user support, to increase the adoption and usage rates, while enabling seamless transaction processing. CBDCs should be built with the ability to adjust to forthcoming developments in technology. The implementation strategy for CBDCs must foresee provisions for system upgrades, to enable continuous system improvement and to maintain adaptability. Technology partners should develop secure digital solutions that can scale for managing high transaction volume, supporting the users' growth. When developing CBDCs, central banks and government authorities need to balance ethical concerns with legal obligations. An equilibrium between privacy concerns and data protection standards must be ensured, while considering ethical aspects in digital currencies' operations. Data protection measures should defend users, informing them about data collection and usage processes utilised by the services. The development of CBDC policies requires stakeholder consultations, to include diverse perspectives and expert knowledge. CBDC development needs the participation of financial institutions alongside technology providers as well as academic expert, civil society organisations and the wider public. Through stakeholder engagement, central banks can build consensus among parties, while identifying

risks and aligning CBDCs with stakeholders' interests. The engagement process brings in a variety of perspectives and expertise, and it reveals potential challenges, while aligning the requirements of all interested parties. Central banks and government initiatives in educational resource development and financial literacy programs may enable users to effectively operate the CBDC ecosystem. All awareness campaigns about CBDCs must include their benefits as well as the risks they present. The documentation must specify user obligations and recommended approaches to conduct secure digital transactions. The public needs to play an active role in CBDC deployment, through research of trustworthy information sources on CBDC developments and issuance, and by engaging in public consultations about their benefits, while maintaining understanding of their potential risks and security vulnerabilities. Consumers can advocate for the establishment of consumer protection policies that prioritise their interests, including clear and transparent mechanisms for dispute resolution and recourse, for victims of fraud or misuse. The promotion of CBDC implementation and utilisation by central banks may represent a step forward for financial inclusion. To achieve widespread adoption and usage of digital currencies, institutions may decide to offer financial incentives like digital wallet subsidies, along with tax benefits for CBDC transactions. The rollout of CBDCs may necessitate either building new digital identification systems or improving the existing ones. Digital identity systems must support secure access and inclusivity for all segments of the population. The digital identity enacted in CBDCs must ensure user privacy and data protection, implementing data usage rules, ensuring transparency and assurance on the respect of privacy regulations for personal information. Central banks may establish partnerships with international organisations, traditional banks and technology providers, to exchange experiences and lessons learned. This collaboration may allow regulators to accelerate CBDC development, helping to overcome common challenges. Government and central banks may create responsive regulatory frameworks which can adapt to technological developments and market shifts, while fulfilling consumer demands. CBDC regulations should remain flexible to cater for future updates. These recommendations may assist the successful rollout of CBDCs, evolving and strengthening the digital currency ecosystem and enabling financial systems to become more inclusive and efficient, maintaining the security and resilience of their operations.

The limitations, applicable to this research, can be grouped as scope restrictions, methodological limitations, and data constraints, and may impact the interpretation of the findings of each paper, and the applicability of the research results to other contexts. Each paper contains its own specific constraints. In the first paper, the comprehensive framework may remain theoretical, and it may not account for all possible factors that can influence the success or failure of a CBDC. The research prioritises specific aspects of CBDC deployment;

however, it might miss alternative elements that require further exploration and study. Despite its comprehensive nature, the framework might have ignored factors capable to affect CBDCs' implementations, thus introducing limitations in its findings' applicability. The effectiveness of the framework is dependent on the quality and availability of the data and information used for the analysis. Due to considerable differences between projects, the available data can vary significantly across different CBDC projects. The framework depends on both the context and unique aspects of each CBDC implementation, for its comprehensive assessment capabilities. The critical literature review inherently carries potential biases and limitations typical of this research approach. The data quality variability within literature reviews might impact the dependability of the conclusions drawn. The research methodology in the paper may introduce bias, as people may interpret policy and socio-economic matters in subjective ways. Researchers following an iterative approach might face inconsistent evaluations, interpreting identical data in different ways.

The second paper relies on publicly accessible information, which may not be comprehensive or current. The second research focuses solely on three launched CBDCs from the Bahamas, Nigeria and China. The selection of three countries for case studies allows for an examination of different CBDC implementation outcomes, affected by their unique regulatory and socio-economic environments, but the resulting findings might not be applicable to other countries, and the paper's conclusions might lack universal applicability, outside of the studied geographic range. The three CBDCs analysed in this research may not represent every possible design and functionality that CBDCs can offer. These research results might not be applied to all CBDCs, as other projects might have diverse design elements and implementation characteristics. This might restrict the relevance of the study to CBDCs possessing similar design elements, in analogous regulatory environments or economic development stages. The research paper examines three specific CBDC projects; their direct comparison might not fully account for the unique considerations and complexities of each CBDC implementation and might be limited by the number of CBDCs launched at the time of writing, not representing all possible CBDCs' implementations. Future research may consider the implementation context as a variable, as it may significantly impact the study outcomes.

The evaluation of technical standards in the third paper might not fully consider various complexities that may appear in practical situations. The effectiveness of the technical standards' evaluation depends upon available data, which might have variable quality and different relevance for asset tokenisation projects. Several studies examine retail CBDCs, however the research landscape concerning wholesale CBDCs remains limited, and presents an area for future investigation. Future research on wholesale CBDCs may explore the

implications on interbank settlements aspects and liquidity management. The papers discuss the importance of cross-border transactions, but there is limited research on CBDCs' interoperability across different jurisdictions. Future research may investigate the CBDCs' cross-border interoperability, in their technical and regulatory aspects, including standardisation efforts, legal harmonisation, and international agreements, to support international trade and to facilitate remittances flows.

A limited number of studies explore the legal and ethical dimensions related to CBDCs. The development of data protection frameworks and privacy-preserving mechanisms for CBDCs calls for additional research. The establishment of a sound legal and regulatory foundation is key for the successful implementation of CBDCs, through the study of the legal implications and challenges associated with CBDCs, including cross-jurisdictional considerations and enforcement frameworks, policymakers may gain insights on appropriate international agreements and best practices. The analysis should include the importance of international organisations and regulatory sandboxes, to develop supportive legal frameworks, through collaborative approaches. The way forward to safeguard data privacy may be represented by advanced cryptographic techniques and decentralised identity solutions. Researchers may decide to examine in detail the implications of CBDCs on conventional banking activities, including deposits and lending, to confirm the potential effects on financial stability. Additional studies on user adoption and usage may be proposed, to verify how individual acceptance of CBDCs is influenced by user perceptions of trustworthiness, benefits and usability. The exploration of user habits and preferences may be necessary, to support the design of user interfaces. A combination of pilot programs and controlled deployments may be beneficial, to evaluate and enhance CBDCs' implementation strategies. This experimental work may generate factual support regarding the practical difficulties and opportunities encountered, when implementing CBDCs. Experiments in CBDC implementations offer a method to control variables, while testing design options and user interfaces as well as regulatory systems.

The consideration of additional CBDCs' case studies, across multiple countries and regions, may improve the research findings. Comparative case studies reveal useful elements and unique difficulties found during the implementation. The developed framework may enable comparative analysis between countries, while uncovering insights from implementation projects. Further studies may be undertaken in areas related to the application of other emerging technologies, exploring how artificial intelligence, and quantum computing can be integrated within the digital currencies' ecosystem, for instance, using artificial intelligence to improve fraud detection and risk management, or quantum computing to future-proof the CBDCs' cryptography. Another important research area for future studies is represented by

the environmental sustainability of CBDCs. The environmental impact may be assessed, by conducting a lifecycle analysis of CBDC systems. The evaluation of energy use and carbon footprint could bring a better perspective on the environmental consequences of CBDC systems and lead future studies to identify potential solutions for the minimisation of CBDCs' footprint (i.e., sustainable design practices, green technologies adoption, and integration with sustainable goals). Future research may investigate how CBDCs impact financial inclusion and inequality among populations, to demonstrate societal benefits across all groups, through models that address marginalised communities' needs, by means of distribution methods and accessibility improvements, combined with focused strategies.

This thesis may positively advance the evolving body of knowledge on CBDCs. The research conducted provided new insights and analysis on CBDCs' design and implementation paths, while addressing valuable gaps in the current body of knowledge. This research may establish groundwork to enable future studies and may provide researchers with a framework and understanding to progress knowledge within this evolving domain. The implementation of CBDCs provide several areas that may be of interest for future research studies. The interoperability of CBDCs necessitate international collaboration among central banks, international organisation and policymakers, to deliver the harmonisation of technical and regulatory standards, and to enable more efficient cross-border transactions, that can drive economic growth. The ethical and legal concerns, related to privacy issues, data protection, and compliance with existing legal frameworks, may become an important area of research, to safeguard individual rights and ethical standards.

Further research, to support the CBDCs' development, may analyse how emerging technologies can be embedded in the design to enhance the functionalities, security and efficiency of CBDCs, supporting new financial solutions. Lastly, the CBDCs' sustainability and environmental impact may become a key area of interest for future research. This series of papers provides researchers and policymakers with both tools and insights that help build analytical knowledge, which can be put into practical use. The policy recommendations identified in this study, may inform the development of more effective and inclusive digital currencies, promoting sustainability and resilience in the financial sector. The innovation journey of digital currencies has only started, and substantial work is foreseen in the future. CBDCs may become an essential instrument to develop a financial system that prioritises inclusion and efficiency, maintaining security, through sustained collaboration and stakeholders' commitment.

GLOSSARY

Access Controls: Security mechanisms that oversee user-system interactions and their connections with other systems and resources.

Atomic Settlement: Simultaneous transfer of two or more assets (such as a token and payment). In this way, all transfers are completed together, or the transfer is cancelled, eliminating the settlement risk.

Automated Market Maker (AMM): A decentralised exchange protocol that price assets and provide liquidity, through dedicated algorithms, enabling peer-to-peer trading in the absence of traditional order books.

Base Money: The aggregate amount of currency in circulation, including commercial bank deposits and reserves held by banks at the central bank.

Blockchain: A blockchain system maintains a transaction record across multiple computers, in a network structure that prevents retroactive alterations of this information.

Central Bank Digital Currencies (CBDCs): National monetary authorities distribute electronic currencies that function as state-backed digital money, to implement modern payment solutions and to expand access to financial services.

Central Securities Depository (CSD): Institution capable to hold financial securities in electronic form and to facilitate clearing and settlement processes, supporting securities' transactions.

Conditional Spending: The ability to establish rules for digital currency spending, based on predefined conditions.

Consensus Mechanism: The process through which the validity of transactions is stipulated in DLT or blockchain networks.

Cross-Border Transactions: Financial trades between a sender and a recipient located in different countries.

Cryptocurrencies: A form of digital currency secured by cryptography and operated in a decentralised way, without a lender of last resort.

Digital Identity: A digital representation of a person or entity, used for KYC and regulatory compliance in digital asset systems, to authenticate and authorise access to digital services.

Disintermediation: The decrease in number of intermediaries in a productive process. In the context of CBDCs, banks and financial institutions represent mediators in financial services.

Distributed Ledger Technology (DLT): Different typologies of system which log transactions at multiple locations and prevent modifications and deletions of recorded data.

Double-Spending: A scenario where funds could potentially be used multiple times from the same CBDC wallet.

Environmental Impact: The consumption of energy, waste generation and carbon emissions generated by a specific activity and/or system.

Fiat Money: Currency acting as legal tender as per government rules that lacks physical asset backing.

Interbank Settlements: The mechanism of settling transactions and concluding transactions among financial institutions.

Interledger Protocol (ILP): Protocol implemented to enable interoperability and to perform payments and transfers over different ledgers and payment applications.

Interoperability: The capability of various systems and applications to operate together, within and across organisational limits.

KYC (Know Your Customer): The procedure by which a business confirms client identities and evaluates their risk potential for illegal activities in business transactions.

Legal Tender: The lawful money that must be accepted for settling debts according to rules.

Monetary Sovereignty: The control by a country of its own currency and monetary policy.

Multi-Factor Authentication: The requirement to authenticate to specific systems through multiple forms, with separate categories of credentials.

Oracles: Additional services that submit data to smart contracts, to enable them to interact with specified events and to trigger determined conditions.

Pilot Phase/Project: Before full release to the market, organisations perform initial testing of their new systems or products, within controlled environments, to discover and resolve existing issues.

Programmability: Functionality through which automated rules and conditions can be programmed, e.g. money can have an expiry date or can be spent only in specific goods, services or in specified areas to encourage spending habits.

Programmable Money: Digital currency with automatic rules or conditions in its code, to perform automated transactions, conditional payments, or policy enforcement.

Quantum Computing: This computing method executes complex calculus through the application of quantum-mechanical occurrences, including superposition and entanglement.

Regulatory Arbitrage: The action of exploiting regulatory variations between nations, to evade adverse legal requirements.

Regulatory Frameworks: Rules and regulations that provide the structure and guidance for companies to operate specific services.

Sandbox: Controlled environment set up and hosted by regulators, where companies can test specific services under eased regulatory requirements.

Scalability: The capability of a system to manage increasing amounts of work as well as its potential for expansion to handle further growth.

Smart Contracts: Contracts which operate through code-based terms and trigger automatic execution on the network.

Throughput: The amount of data processed through a system, during a defined period.

Tiered Remuneration Schemes: A system in which different interest rates, or other incentives, are applied to different sums of money or transactions.

Time-Limited Currency: Digital money that becomes invalid once its predetermined expiry period passes.

Transaction Fees: Charges imposed by a financial institution for processing a transaction.

Two-Tier Distribution Model: Distribution model for CDBC's, where the central bank issues digital currency to authorised intermediaries, who perform customers' identification and perform CDBC's transactions on behalf of end users.

User Interfaces (UI): A User Interface serves as interactive bridge between a user and computer software or applications.

Zero-Knowledge Proofs: A technique that lets one entity demonstrate knowledge of a value to another party, without transmitting any additional information beyond the proof of possessing that value.

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