Digital Currency Development and the Impact of Central Bank Digital Currency on International and National Settlement Systems

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ABSTRACT

This thesis consists of three essays on digital currency, with a particular focus on central bank digital currencies (CBDCs). These essays progressively narrow in focus, starting with a broad overview of digital currency research, then moving to an empirical investigation of global CBDC practices, and finally, narrowing the scope to explore an in-depth case study of China's CBDC and its global implications.

Essay one provides a comprehensive review of the evolution of digital currency, focusing on two primary categories: private sector digital currencies, represented by Bitcoin and Ethereum, and CBDCs. This literature survey suggests that the future viability of private digital currencies is increasingly constrained by regulatory hurdles, market volatility, and their inadequacies as stable stores of value and mediums of exchange. Meanwhile, CBDCs are emerging as a predominant trend in the digital currency landscape, exhibiting broader application potential. By investigating the potential benefits and challenges associated with CBDCs, this study suggests that there is a critical need for global consensus and cooperation in the development and framework construction of digital currencies.

Essay two assesses the potential influence of CBDCs development on currency's invoicing capability in international trade. Based on the theories of firms' profit maximization, trade elasticity and sticky prices, this study constructs a model of currency invoicing power, including CBDC announcement year as the shock for moderating effect. Utilizing a sample of the top 50 countries, covering the period from 2005 to 2022, this study finds that the development signal of a country's CBDC significantly strengthens the exchange rate pass-through, suggesting an enhanced

currency invoicing power, and this effect is even stronger in countries that have piloted CBDC programs. Mechanism analyses reveal that the currency invoicing power improved through reducing exchange rate volatility and increasing currency liquidity in international foreign exchange market. These effects make the currency a more attractive choice for international invoicing. Our research may provide insights for policymakers that promoting and accelerating the development of CBDCs can promote the use of national currencies in international trade, as well as improving national currency internationalization.

Essay three examines the conditions and impediments for the implementation the digital Chinese currency (called e-CNY) in China, where a rapidly evolving digital payment landscape coexists with traditional currency transactions. Utilizing provincial-level panel data from 2011 to 2021, this study analyses the potential impacts of "Breadth of Digitalization Coverage" and "Digitalization Level" on the supply and demand dynamics of e-CNY within the framework of digitalization development. The findings reveal that an increase in digitalization correlates with a reduction in the supply and demand for physical currency, indicating that digitalization has paved the way for adopting e-CNY. Further analyses reveal that the penetration of smartphones and the growth of e-commerce have been instrumental in broadening digitalization coverage and the level of digitalization. The study foresees that despite the digitalization of wallets and payment scenarios has laid a solid foundation for implementing e-CNY, establishing an efficient and secure e-CNY payment ecosystem will still require a development period of several years.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE INTRODUCTION

1. Introduction

Over the centuries, currency has undergone profound transformations, evolving from tangible assets such as the gold standard to the intangible yet ubiquitous physical currency, and further into the realm of electronic money facilitated by technological advancements such as the internet. The transition from paper currency to digital currency represents a milestone in the history of currency. This progression has set the stage for the advent of digital currencies, driven by innovations of blockchain and cryptography, which underpin private sector digital currencies such as Bitcoin and Ethereum. The rise of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, and cloud computing has paved the way for the development of fiat digital currencies. These technologies are widely used in internet applications, e-commerce, mobile payments, and digital finance. The latest evolution in this trajectory is the emergence of CBDCs, developed in response to the challenges and opportunities posed by private digital currencies. These digital forms of state-backed currency are poised to enhance payment efficiency, bolster financial stability, and promote financial inclusion, signaling a new era in the evolution of money.

Although the super-sovereign digital currency Diem, formerly known as Libra, ultimately failed in its launch, it garnered significant attention from sovereign states around the world. The potential impact of digital currencies on the global financial system remains an open and compelling area of research. In response to the potential influences, over 80% of countries worldwide are actively exploring CBDCs (Boar et al., 2020), with numerous private entities also joining this race. In recent years, authorities have initiated research into the digitalization of their currencies, with several countries and regions piloting their local CBDCs, including China, India, Russia, France, Singapore, Saudi Arabia, and United Arab Emirates (CBDC Tracker, 2024). Additionally, there has been a notable rise in international collaborative CBDC projects, with multiple countries developing joint initiatives, such as mBridge, Jasper-Ubin, and LionRock. These projects demonstrate a growing trend towards interoperability among digital currency systems. Despite these advancements, most CBDCs remain in the pilot or even conceptual stages, and a fully developed and widely deployed digital currency has yet to emerge. The research in this area remains in its preliminary stages, leaving many issues to be explored.

2. Structure of the thesis

This thesis consists of three essays on digital currency, with a particular focus on CBDCs. These essays progressively narrow in focus. To begin with, Essay one provides an overview of the evolution of digital currency from a broad perspective. As more and more sovereign nations reach a consensus that it is beneficial to have their own digital currency, Essay two narrows the scope from digital currency in general to CBDC. It further explores the potential impact of CBDCs on international invoicing and how CBDCs can reshape global financial settlement systems. Additionally, Essay three also focuses on the domestic applications of CBDCs, using China as a case study.

The structure of this thesis is organized as follows.

Chapter one introduces the research background and motivations, explaining the focus on digital currency and the selection of CBDCs the research object. It also outlines the structure of the thesis and the possible contributions we may provide.

Chapter two contains Essay tne, a literature survey that systematically investigates and analyses current research from two perspectives: private sector digital currency (cryptocurrency) and central bank digital currency (CBDC). This survey provides a relatively comprehensive review of the evolution of digital currency. Initially, Bitcoin and other cryptocurrencies led the digital currency movement. However, as central banks globally explore and implement CBDCs, these currencies are seen as promising tools for enhancing payment system efficiency, financial stability, and financial inclusion. The survey finds that private digital currencies face challenges such as regulatory hurdles, market volatility, and inadequacies as stable stores of value and mediums of exchange. In contrast, CBDCs are emerging as a dominant trend in the digital currency landscape, offering broader application potential.

To further explore the preliminary conclusion in Chapter two that central bank digital currency represents the likely future of digital currency, Essay two in Chapter three assesses the impact of CBDC development on a currency's invoicing capability in international trade. Drawing on Amiti et al. (2022) and Gopinath et al. (2020), we construct a model of currency invoicing power, based on the theories of firms' profit maximization, trade elasticity and sticky prices. Utilizing a large sample of the top 50 countries from 2005 to 2022, we find that the development of a country's CBDC significantly strengthens the transmission of bilateral exchange rate changes between exporting country and importing country into changes in traded commodity prices, suggesting an enhanced invoicing power of the country's currency. Moreover, this effect is even stronger in countries that have piloted CBDC programs.

The third essay in Chapter four is a policy paper that examines the conditions and impediments for the implementation the CBDC, using China as a case study, where a rapidly evolving digital payment landscape coexists with traditional currency transactions. Utilizing provincial-level panel data from 2011 to 2021, Essay three analyses the potential impacts of "Breadth of Digitalization Coverage" and "Digitalization Level" on the supply and demand dynamics of China’s digital currency, electronic Chinese Yuan (e-CNY), within the framework of digitalization development. The findings reveal an increase in digitalization correlates with a reduction in the supply and demand for paper currency, indicating that digitalization has paved the way for adopting e-CNY. Further analyses show that the penetration of smartphones and the growth of e-commerce have been instrumental in broadening digitalization coverage and the level of digitalization.

Chapter five concludes by summarizing the key findings of each of the three essays, discussing the limitations of this thesis, and then offering suggestions for potential future research.

3. Contributions of the study

Overall, this thesis provides a comprehensive discussion of digital currency, exploring the topic from both the theoretical and practical application perspectives, as well as examining the topic through both international and domestic case studies.

Essay one systematically maps the development of digital currency research, reviewing existing research achievements in this cutting-edge field. Specifically, from the perspectives of private digital currencies and central bank digital currencies, this review outlines the digital currency’s developmental framework, constructing a research map to facilitate subsequent research. It shows that CBDCs represent a crucial direction for the future development of digital currencies. Moreover, the review examines and compares the controversial viewpoints in the field, identifying current research gaps and potential future discussion directions. Additionally, it creatively summarizes the theoretical foundations of three different types of digital currencies: cryptocurrencies, stablecoins, and central bank digital currencies, providing a solid theoretical foundation for new research. Furthermore, this review summarizes the experiences of different countries and regions regarding digital currency policies and legal regulations, offering valuable policy recommendations.

Essay two makes contributions in three areas. First, it empirically provides new, evidence-based insights into the growing interest in how the development of CBDCs can impact the existing international monetary system. By using a broad sample, this study enriches currency pricing theory from a global perspective, explaining how CBDCs influence the invoicing currency selection in international trade. Second, it fills a gap in the literature by detailing the pathways through which CBDCs can influence currency invoicing capability. This study offers the first empirical evidence on the view that the development of a country's CBDC significantly enhances its trade invoicing power by mitigating exchange rate volatility and increasing currency liquidity in international foreign exchange markets. Third, the study provides a new perspective on global currency diversity, offering valuable insights for policymakers. The findings suggest that developing CBDCs significantly enhances national currency invoicing power, implying the development of CBDCs is a strategic tool for increasing national currency internationalization. Promoting and accelerating CBDC development can increase the use of national currencies in international trade.

Existing studies on CBDCs predominantly focus on theoretical frameworks, almost certainly due to data limitations. Essay three contributes to the literature by providing an empirical investigation into CBDCs. It enriches the literature on the development and implementation of CBDCs, where empirical analyses are notably scarce. Additionally, this study contributes to the expanding body of knowledge on

CBDCs by focusing on China's e-CNY. Considering that China's digital infrastructure is state-owned, in contrast to the Western model of privatization, our analysis examines the infrastructural factors influencing digitalization coverage and levels in China. This provides insights that could assist in the development and implementation of similar digital currencies globally. Moreover, by examining the relationship between digitalization development and paper currency, we aim to forecast the potential supply and demand for the upcoming e-CNY. This may offer valuable insights for policymakers and financial institutions navigating the new terrain of monetary digitalization in countries with similar electronic payment ecosystems.

CHAPTER TWO ESSAY ONE

A Survey on the Digital Currency Revolution – Its Evolution and Implications

Abstract

This chapter reviews some 20 years of the literature on digital currencies, with a focus on its two key categories: private-sector digital currencies and central bank digital currencies (CBDCs). After reviewing a total of 160 academic papers, the findings indicate that the long-term viability of private-sector digital currencies is increasingly constrained by regulatory disorientations and their inherent limitations as stable stores of value and reliable mediums of exchange. Conversely, CBDCs are emerging as a predominant trend in the digital currency ecosystem with broader application potential. By critically examining of the mainstream perspectives and ongoing controversies, this literature survey identifies several research gaps for future exploration.

Keywords: digital currency, cryptocurrency, central bank digital currency

1. Introduction

We are currently witnessing a transformative shift towards digital currency, including cryptocurrencies and central bank digital currencies (CBDCs). Advances in digitalization and disruptive technologies, particularly the emergence of blockchain, distributed ledger technology, and smart contract[1] (Szabo, 1994) provide strong technical support for the development of digital currencies (Li & Kassem, 2021). These technological breakthroughs are not only reshaping the form of traditional currency but are also having a deep impact on the structure of the global financial system. In recent years, global economic instability, especially the 2008 financial crisis and subsequent economic fluctuations, has highlighted the weaknesses of centralized monetary control, such as the risks of bank failures, liquidity crises, and reliance on traditional financial intermediaries, thus driving research and development of decentralized alternatives like digital currencies (Gaies et al., 2021). The COVID-19 pandemic has contributed to the increased adoption of digital payments, further raising global interest in DeFi assets and conventional currencies (Yousaf et al., 2022).

The importance of digital currency research lies not only in its technological innovation but also in its potential for widespread economic impact. Cryptocurrencies are often considered as the original form of digital currency, however, the interest in issuing CBDCs has surged recently among countries. Many countries globally have been advancing the development of CBDCs into the pilot phase. Central banks are

[1] Smart contract, first proposed by jurist Nick Saab in 1994, is a code running on the blockchain in order to replace centralized judicial jurisdiction with blockchain technology, especially applying to the case that multiple participants are in different jurisdictions.

motivated to develop CBDCs to improve the financial inclusion, increase monetary policy effectiveness (Umar, 2025), address competition from cryptocurrencies, and maintain monetary sovereignty (Auer et al., 2022). The International Monetary Fund (IMF) and other international institutions have already begun to focus on the policy challenges and regulatory needs that digital currencies may bring. As technology continues to advance, the potential advantages and challenges of digital currencies are becoming increasingly important. Given this context, digital currencies are not only a major innovation in the fintech sector but have also become a focal point for economists and policymakers. To develop a comprehensive and in-depth understanding of the research in this field has become increasingly important.

This paper offers a comprehensive and systematic exploration of the cutting-edge field of digital currency research, providing a detailed overview of the existing academic literature in this area. By focusing on both private digital currencies and central bank digital currencies, the review constructs a digital currency's developmental framework, providing a research map to facilitate subsequent research. A central argument of this survey is that CBDCs represent a pivotal direction for the future evolution of digital currencies. Through a critical examination and comparison of the divergent and often controversial viewpoints, the study identifies current research gaps that have yet to be addressed.

In addition to mapping the current research landscape, the review makes a novel contribution by summarizing the theoretical foundations of three distinct types of digital currencies: cryptocurrencies, stablecoins, and central bank digital currencies. It provides a solid theoretical foundation that can support new research in this rapidly evolving field. Furthermore, the study delves into the specific characteristics and implications of each type of digital currency, offering a nuanced understanding that is crucial for both theoretical advancements and practical applications.

Finally, the review summarizes the central bank digital currency policies and legal regulations implemented by various countries and regions, offering a set of valuable policy recommendations. These recommendations are especially pertinent for policymakers as they navigate the challenges and opportunities associated with digital currencies, ensuring that the insights offered are both practical and actionable.

As a novel topic, the existing literature on digital currency nowadays is fragmented and there is a lot of inter relationships that require to be very clearly defined and explained. In this context, we conduct a literature review on digital currency as a survey in Chapter two. This chapter is structured as follows: after the introduction, Section 2 innovatively summarizes the upcoming revolutionary changes to conventional currency brought about by applied disruptive digital technologies but from the financial perspective beyond technology. Next, Section 3 and Section 4 carefully organize current research on digital currency in two ways that issued by private sector and public sector, respectively. Finally, we conclude with a general summary and implications in Section 5 and discuss the likely future trends of digital currency.

2. Evolution of digital currency

Currency has evolved from physical forms like commodity and metal money to the introduction of fiat currency, eventually transitioning to digital formats (refer to Figure 2.1). The advent of physical currency marks a significant milestone in the history of currency, transitioning from physical to credit money, backed by state endorsement. The prevalence of e-payments also paved the way for the future digital currency era, as consumers became accustomed to electronic transactions.

Figure 2.1 An overview of currency evolution

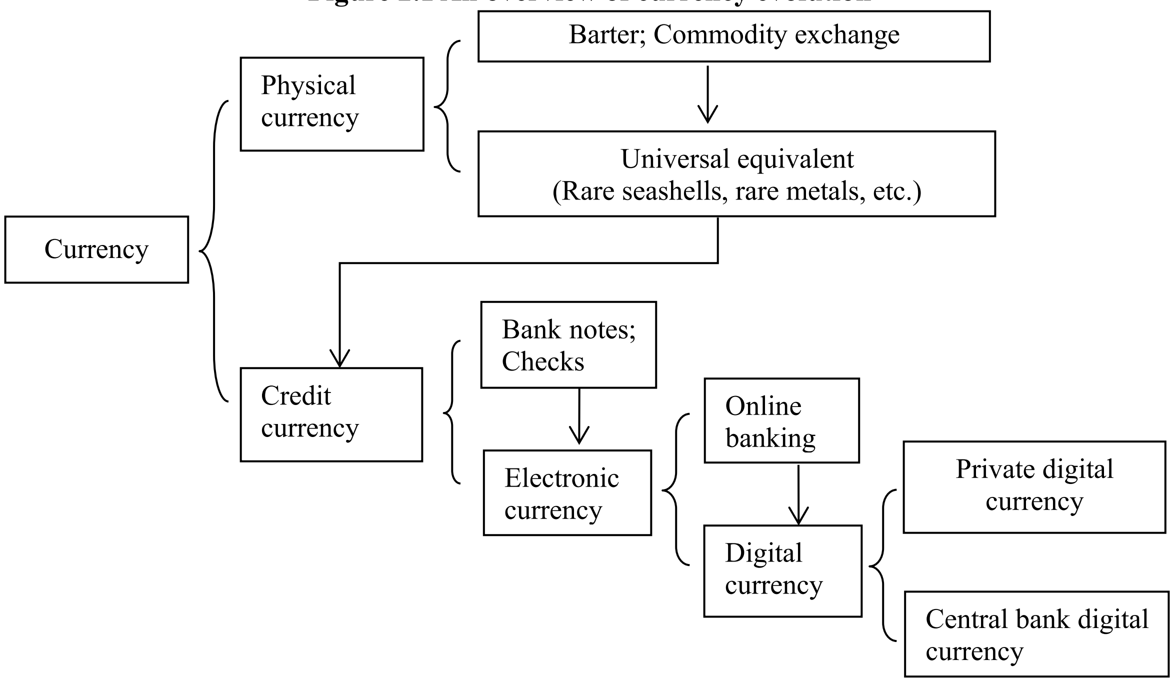

Figure 2.1 provides a brief overview of the evolution of currency. It starts with barter, where goods were directly exchanged despite challenges of coincidence and making change. With developments in metal smelting, gold became a preferred currency due to their durability and ability to store value. However, the limited gold supply made the 1717 Gold Standard unsustainable. The 1944 Bretton Woods Agreement replaced it with the U.S. dollar, addressing the limitations of metal currency. After the Great Depression, fiat money and paper currency, supported by anti-counterfeiting measures, became widespread. Paper money overcame the limitations of physical currency, enabling a more flexible money supply that boosted global trade and growth. Electronic money emerged in the 1950s with the first credit card from Franklin National Bank, leading to widespread adoption of bank cards. While e-money doesn't change the nature of money, it converts paper currency into electronic form, speeding up circulation and reducing costs.

2.1 Digital currency history

Except for several anonymous cryptocurrencies regarded as the predecessors for Bitcoin, the development of digital currency has experienced periods of cryptocoins, stablecoins, and CBDCs.

2.1.1 Pre-bitcoin era

Bitcoin is often regarded as the father of cryptocurrencies, heralding the arrival of digital currency (Cheung et al., 2015). However, the first blockchain-like protocol was proposed by Chaum (1979) in his dissertation, it was then brought into Bitcoin by Satoshi (Nakamoto, 2008). It can be noted there are many cryptocurrencies with similar core concepts and ideas that emerged before Bitcoin. In the Pre Bitcoin Era, E-cash (Chaum, 1983) without blockchain technology can be seen as the earliest form of cryptocurrency, which is an anonymous cryptographic electronic money used as a micropayment system at one U.S. bank. Then DigiCash governed by a number of cryptographic protocols appeared. It allowed for withdrawing notes from a bank, and sending payments one another. Chaum (1983) is a pioneer who invented the blind signatures technologies that are used in both Ecash and DigiCash. Bitcoin's another precursor B-money (Dai, 1998) was an anonymous, distributed electronic cash system that emphasized peer-to-peer transactions and has already integrated a proof-of-work scheme in one way. During the pre-bitcoin era, numerous cryptocurrencies emerged and vanished swiftly. These cryptocurrencies struggled to gain mainstream acceptance, primarily because they relied on regulation, which inherently limited their growth.

2.1.2 Cryptocoin

The precursor to Bitcoin inspired its creation and contributed to the development of its underlying technologies. Typically, Bitcoin is the first truly decentralized cryptocoin and subsequently evolved into the first cryptocurrency. Bitcoin uses a UTXO (Unspent Transaction Output) database to prevent the issue of double spending (Karame et al., 2012), which was a problem faced by earlier digital currencies. The UTXO system tracks unspent transaction outputs, ensuring that each bitcoin is only spent once. Additionally, Bitcoin improves on Bit Gold's weakness to prevent collusion among miners with its renowned consensus mechanism. Moreover, Jeff Garzik (2018), one of the core developers of the Bitcoin protocol, emphasizes that Bitcoin leverages peer-to-peer technology to operate without a central authority. Its open-source design provides functionalities that challenge traditional financial systems and pave the way for future advancements in blockchain technology.

Another notable blockchain is Ethereum, designed to facilitate a range of activities and applications through smart contracts. Generally, blockchain technology can support alternative currencies by making them trustworthy, resistant to attacks, and enhancing their security. However, as blockchain scales, it exhibits shortcomings such as limited scalability, restricted block memory, and difficulties in developing various financial applications. Additionally, an increasingly congested blockchain leads to prolonged transaction confirmation times and high energy consumption (Li et al., 2019). Since Bitcoin successfully attracted significant popular attention, thousands of imitator cryptocurrencies, known as Altcoins (alternative variants of Bitcoin such as Ethereum, Litecoin, Ripple, etc.), have been continuously created. These altcoins aim to overcome or optimize various shortcomings of Bitcoin from different perspectives.

Technically, blockchain, characterized by decentralization and consensus mechanisms [1], can be viewed as a decentralized ledger that concurrently records transactions on multiple computers (Kshetri, 2021). The most common voting-based consensus mechanisms applied in cryptocurrencies are POW[2], POS[3], DPOS[4], PBFT[5], DBFT[6], and COSMOS[7]. Initially, cryptocurrency used POW, relying on computational power for mining. This led to high energy consumption and centralization issues, because miners with greater computational power had an advantage in competing for voting rights and earning more coins (Li et al., 2019). To address this, POS was developed, shifting from computational to coin-based voting, akin to shareholder voting in companies. Although POS is more energy-efficient, it remains vulnerable to attacks by large funds, especially for those low-value cryptocurrencies. Some cryptocurrencies use a hybrid POW+POS mechanism to combine benefits. DPOS, used in consortium blockchains, involves nodes voting to select super-nodes for block generation, while PBFT and DBFT are used in private and delegated blockchain networks for efficient consensus. COSMOS, similar to PBFT, aims for faster transactions and improved blockchain interoperability.

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[1] Consensus mechanism based on "best effort basis" is introduced to make digital currency hard to tamper with regarding any trading information.

[2] Proof of Work (POW): A mechanism relying on computational power for mining, where miners with greater resources are more likely to mine blocks.

[3] Proof of Stake (POS): A mechanism that uses the amount of cryptocurrency held for voting and mining, akin to shareholder voting in companies.

[4] Delegated Proof of Stake (DPOS): A consensus algorithm for consortium blockchains where nodes vote to select supernodes responsible for block generation.

[5] Practical Byzantine Fault Tolerance (PBFT): A consensus mechanism typically used in private blockchain applications that allows for fast transmission.

[6] Delegated Byzantine Fault Tolerance (DBFT): A variation of PBFT used in delegated blockchain networks for efficient consensus with fewer nodes.

[7] COSMOS: A consensus mechanism similar to PBFT, focused on achieving faster transaction speeds and improved interoperability between blockchains.

2.1.3 Stablecoin

The market prices of cryptocurrencies are highly volatile driven by various factors, such as market sentiment, policy changes, supply and demand dynamics, black swan events, and speculative behavior. This price fluctuation makes it difficult for them to serve as a store of value, medium of exchange, or unit of account in the same way as traditional currencies (Giudici et al., 2020). Such volatility-affected cryptocurrencies cannot fulfill the functions of traditional currencies. Stablecoins were introduced to address this issue, especially during bear markets when investors aim to minimize losses by converting their digital assets into stable currencies (Wang et al., 2020). Stablecoins are diverse and can be categorized into three main types (USDC Center, 2018): fiat-collateralized stablecoins[1], such as USDC and USDT, which are pegged to the U.S. dollar and Venezuela's Petro, respectively; crypto-collateralized stablecoins[2]; and algorithmic collateral-free stablecoins[3].

Among those cryptocurrencies and stablecoins, there are three types of blockchain: public blockchains, private blockchains, and consortium blockchains (also known as hybrid blockchains), each differing in decentralization and openness. Private chains sacrifice decentralization for scalability, while public chains have a high degree of decentralization but are difficult to trade instantly. Specifically, public blockchains can be joined without any permission and maintain stability through the value of the token

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[1] Fiat-collateralized stablecoin aims to provide price stability by pegging the token to a reserved fiat currency at a 1:1 ratio.

[2] Crypto-collateralized stablecoin achieves price stability by pegging the token to a cryptocurrency, often with excess collateral.

[3] Algorithmic collateral-free stablecoin maintains price stability through smart contracts that control supply and demand without relying on underlying collateral, such as Basis and Carbon.

in circulation, which is primarily derived from the credit endorsement of participating nodes. Famous examples include the Bitcoin and Ethereum blockchains. Private blockchains are created by specific organizations and offer advantages such as fast transactions (since nodes trust each other, reducing verification time), low cost, and privacy protection. However, they sacrifice decentralization to some extent.

Additionally, because they can freely set access and data reading rights, their security is weaker. Consortium blockchains are jointly managed by several institutions or organizations. Each of them runs one or more nodes. The data in consortium blockchains only allows the institutions in the system to read and send, and they record data together. The transaction speed and decentralization degree of consortium blockchains are intermediate between public and private blockchains. Additionally, some articles consider both fully private blockchains, such as MUFG launched by UFJ (Bank for International Settlements et al.) and consortium blockchains such as eTrade Connect, R3CEV (allowing banking organizations to share data one another), and ChinaLedger, are considered as private blockchains.

Table 2.1 Representative cryptocurrencies worldwide

Items	BTC	ETH	EOS	USDC
Time of Block	10 minutes	15 seconds	3 seconds	Not available
Money supply	21 million	72 + 18.72 million per year	1 billion	Stablecoin pegged dollar
Distributed Consensus	POW	Aiming from POW to POS	DPOS	POW
Ledger	Transaction-based Ledger	Account-based Ledger	-	-
Data Structure	Merkle Tree	Merkle Patricia Tree	-	-
Blockchain Type	Public Blockchain	Public Blockchain	Public Blockchain	Private Blockchain
Technical framework	Decentralized	Decentralized	Semi- Decentralized	Semi- Decentralized
Cost of Use	Service fee 0.001 BTC	Gas fee 0.005 ETH	Free	Almost free
Payment Scenario	Few	Smart Contract	Operating System	Cross Border Transfer
Execution Time	60 Minutes	6 Minutes	Near-instant	Near-instant

Proof of Work (POW): A mechanism relying on computational power for mining, where miners with greater resources are more likely to mine blocks.
Proof of Stake (POS): A mechanism that uses the amount of cryptocurrency held for voting and mining, akin to shareholder voting in companies.
Delegated Proof of Stake (DPOS): A consensus algorithm for consortium blockchains where nodes vote to select supernodes responsible for block generation.
Merkle Tree: A data structure used to securely verify the integrity of large sets of data. It is a tree in which every leaf node is a hash of a data block, and every non-leaf node is a hash of its child nodes, enabling quick verification of data integrity.
Merkle Patricia Tree: A modified version of the Merkle tree. It is used in Ethereum to store key-value pairs, providing a compact and efficient way to represent and validate the state of the blockchain.

2.1.4 Central bank digital currency

In 2014, the first CBDC was issued by the central bank of Ecuador. However, it ultimately failed in 2018 due to the severe domestic inflation and widespread mistrust in the central bank. The resulting reluctance to use the national currency led to low circulation of the CBDC. Similarly, Denmark faced opposition to issuing a CBDC due to its fixed exchange rate with the Euro and open capital account, which prevent it from implementing an independent monetary policy to manage cross-border capital flows potentially using their CBDCs. Consequently, Denmark declared it will not issue a CBDC in the future (Denmark National Bank, 2017). Germany has also expressed concerns, fearing that a digital Euro could pose risks to its banking sector. The United States has shown hesitation and deliberation on this matter, reflecting a dilemma regarding this issue in the early stage. The stance has shifted from opposition to active, and has now developed several proposals under discussion. For instance, the scheme of “digital dollar wallet” proposed by a democratic senator (Sen. Brown, 2020) to stimulate the economy amid the COVID-19 pandemic; the “Digital Dollar Project white paper” to maintain the dollar's dominance; and the notable Libra project initiated by Facebook. However, none of these proposals has been adopted so far. The Federal Reserve evaluates the potential role of a CBDC in the payment system but has not released any detailed official plans for a digital dollar (Wong & Maniff, 2020). Adopting a cautious approach, the UK, Finland, and the European Central Bank are concerned about the possible adverse impacts on macroeconomic stability.

Alternatively, many countries are actively advancing their research on CBDCs, particularly those with well-developed electronic payment environments. Norway and Sweden are making significant progress in this area. Specifically, Norway has developed a preliminary scheme called “A CBDC in the form of register-based token money” (Norges Bank, 2018, 2019) and an alternative scheme termed “a closed account-based solution offering the possibility of storage on a physical device,” which resembles systems such as PayPal. Sweden proposed two editions of digital cash in 2017: the value-based e-krona and the register-based e-krona, designed to complement physical cash (Sveriges Riksbank, 2017, 2018, 2020). Singapore and Canada are going to launch their CBDCs called Ubin (Monetary Authority of Singapore, 2017) and Jasper on Ethereum public blockchain as a private chain. Countries such as China, Russia, Saudi Arabia, and the United Arab Emirates have made notable progress in advancing their CBDC pilot programs (Atlantic council, 2024). The joint report by seven major central banks (Bank for International Settlements et al., 2020) marks a significant milestone in the development of CBDCs. This research achievement, conducted by the joint group, explains the consensus on core features and basic principles of CBDCs and highlights the impact of cross-border payment systems.

In summary, reflecting on the failed pre-Bitcoin cryptocurrencies, their lack of attractiveness and success can be attributed to the limited public understanding of cryptocurrency at the time. However, Bitcoin's current success has catalyzed significant investment of capital, personnel, and technological resources into the digital currency sector, fostering rapid development. Despite this progress, the inherent pricing volatility of cryptocurrencies renders them unsuitable for daily transactions. Stablecoins mitigate some of these issues but still face challenges in gaining quick acceptance from the public. The payment scenarios for both cryptocurrencies and stablecoins have always been quite limited. In contrast, CBDCs, designed specifically for payments, show promise for superior performance in this area (refer to Table 2.2).

Table 2.2 Performance comparison for digital currencies

Items	Bitcoin and Altcoins	Stablecoins	CBDCs
Cases	BTH, ETH, etc.	USDT, etc.	e-CNY, etc.
Store of Value	√	√	√
Volatility Proof	×	√	√
Massive User Base	×	×	√
Rich Payment Scenarios	×	×	√

2.2 Fundamental theory development

2.2.1 Cryptocurrency: Austrian School of Economics Theory

The core principles of economic theories provide valuable explanations into the behaviors of digital currencies. The decentralized nature of many private sector digital currencies aligns closely with the Austrian School of Economics, particularly its anarchist monetary theory, as championed by economists such as Hayek (1978) and Mises (2007). Contrary to the Keynesian School Theory (Keynes, 1936), which advocates for substantial government intervention in regulating the money supply, the Austrian School posits that minimal governmental interference is preferable. It contends that the most effective currency should emerge organically through free-market competition.

Hayek (1978) suggests that sovereign, government-backed currencies may become obsolete, potentially replaced by private-sector-issued currencies. These currencies would not be bound by national borders but rather function as "super-sovereign" entities, operating independently in a global, state-free framework. Prominent examples of such decentralized digital currencies include Bitcoin and Libra.

2.2.2 Stablecoin: Optimal Currency Area Theory

The mechanism of stablecoins is fundamentally based on the Optimal Currency Area Theory (Mundell, 1961) and the Linked Exchange Rate System Theory. The Optimal Currency Area Theory suggests that regions with similar economic structures and policies benefit from sharing a common currency (Mundell, 1961). In the context of stablecoins, this theory implies that digital currencies pegged to stable assets, such as fiat currencies, can provide economic stability and reduce exchange rate volatility. Linked Exchange Rate System Theory further supports this mechanism by illustrating how stablecoins, particularly fiat-collateralized ones such as USDC, operate similarly to fixed exchange rate systems. However, this pegging mechanism also means that such digital currencies cannot independently implement monetary policies. They rely on the stability and monetary policy of the underlying fiat currency, limiting their ability to respond to economic changes autonomously.

2.2.3 Centralized digital currency: Keynesian School Theory

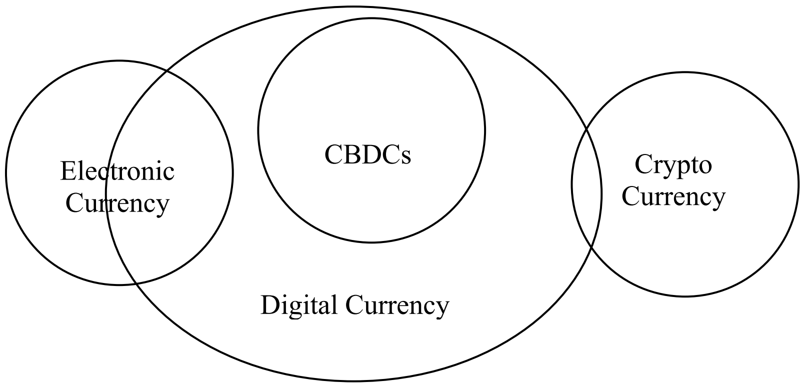
The Keynesian (1937) provides theoretical support for centralized digital currencies. Proponents argue that governments ought to regulate and control the circulation of digital money and utilize monetary policy to stimulate or temper economic activity, thereby maintaining economic stability. By adjusting interest rates, controlling money supply, and implementing fiscal policies, governments can address economic fluctuations and ensure sustainable growth. The Quantity Theory of Money

(Fisher, 2006), which link money supply to price levels and emphasize the role of sovereign currency issuers, provides a significant theoretical foundation for analyzing and developing CBDCs.

2.3 Developing connotations

Digital currency is continuously evolving to encompass not only partially electronic currencies (unencrypted electronic cash that existed before cryptocurrency) but also certain cryptocurrencies widely accepted for purchasing goods and services, as well as CBDCs (refer to Figure 2.2). Despite the emergence of digital currency, there is still no consensus on its standard definition. This section aims to examining the developed concept of digital currency by discussing its definition, taxonomy controversy, and coming innovative characteristics.

Figure 2.2 Components of digital currency



2.3.1 Varied definitions

Digital currency is not a well-defined term yet. Scholars from diverse perspectives have proposed various definitions, reflecting their differing expectations for its future. Among them, these exist in some variants, such as virtual currency (Bolt & Van Oordt, 2020), private digital token (Wu et al., 2019), cryptocurrency and central bank cryptocurrency (Bech & Garratt, 2017), central bank digital currency.

Authorities have formed a rudimentary concept on centralized digital currency. The European Central Bank considers digital currency to be the digitized claim to the liabilities of the central bank, akin to paper currency in circulation.

Scholars differentiate their understanding from the perspective of the form of currency. Hoang et al. (2023) defines digital currency as currency in electronic form used to store value and circulate as cash, including electronic currency. To develop this statement, Giudici et al. (2020) provides a detailed analysis of the distinctions between electronic currencies and cryptocurrencies, exploring their different technological foundations and use cases. Similarly, a report from CPIM (Committee on Payments and Market Infrastructures, 2015) provides an early conceptual analysis of digital currency, defining central bank digital currency as electronic central bank liabilities used in peer-to-peer exchanges. Bank of England (2021) notes that CBDC would be a new form of digital money issued by the central bank for households and businesses, designed to complement cash and bank deposits rather than serve as their replacement. Mu (2020), the director of Digital Currency Research Institute of China, states that CBDC is a payment instrument characterized by value, convertibility, and legal tender status. It is equivalent to conventional banknotes and coins but can support additional scenarios, such as offline payments with a "loose coupling function" among bank accounts.

Besides, some advocates view digital currency as a virtual currency. Bolt and Van Oordt (2020) note that digital currency encompasses both virtual currency and e-money.

Additionally, Scholars distinguish the connotation of digital currency from the perspective of its technical principles. The Federal Reserve has highlighted the distinction between account-based and token-based systems in the context of digital currencies (Lee et al., 2020) , noting that the Digital Dollar project exemplifies a token-based system. In these systems, tokens represent digital units of value that can be transferred directly between parties without intermediaries. In contrast, account-based digital currencies require the verification of the account holder's identity, typically through physical devices such as smartphones.

2.3.2 Taxonomy controversy

The ambiguous definition of digital currency has led to interest in its fundamental functions and taxonomy. The controversy surrounding the taxonomy of various digital currencies, particularly those in the private sector, complicates the precise definition. The prevailing statements typically classify digital currencies into two categories: novel currency and digital financial assets.

(1) Substitute money

Considering the functions of currency—medium of exchange, unit of account, and store of value—research suggests a consensus that central bank digital currency could represent a new form of money (Committee on Payments and Market Infrastructures, 2018). Some research views cryptocurrencies as substitutes for real money in specific fields, particularly the illegal market where drugs and guns are sold exclusively for Bitcoin (Foley et al., 2019). Despite the absence of specific issuing institutions or intrinsic commodity value, digital currencies can function as traditional currency if widely accepted. Alvarez et al. (2023) examine the potential of Bitcoin to serve as a medium of exchange and substitute for legal tender. The study finds that despite the government efforts to promote Bitcoin usage, its adoption has been limited and is declining over time. Hui et al. (2020); Selgin (2015) believe Bitcoin can act as a "synthetic commodity money" between fiat money and a crypto-commodity used for trading and investment purposes.

(2) Digital asset

Many analysts assert that digital currencies cannot fulfill the functions of money and exhibit many characteristics of financial asset. Participants view Bitcoin more as a convertible asset than a trading medium. In the U.S., cryptocurrencies are treated as property for taxation purposes, independent of central bank measures (John & Kumhof, 2016). Yermack (2024) argues that Bitcoin has little significance as an exchange medium due to the speculative nature of 80% of Bitcoin transactions and its volatility, which exceeds that of high-risk stocks, hindering its function as a unit of account and store of value. By analyzing participant behavior and motivation, Glaser et al. (2014) conclude that Bitcoin is not suitable as money, as it is only accepted by a minority of merchants.

While some argue that cryptocurrency could represent a return to the gold standard, this is challenging. During the gold standard era, gold mining could not keep up with expansion of social wealth, and mining capabilities varied across countries. In contrast, digital currencies operate on universally accessible technology and are easily divisible. However, Bitcoin, often seen as a potential safe-haven asset similar to gold, has distinct characteristics that pose challenges. Bitcoin has fundamental differences from gold in terms of market structure and trading behavior. Its 24/7 trading with relatively low daily volumes (Feng et al., 2018b) and lack of trading halts can lead to heightened volatility and market instability. The opening price is typically close to the previous day's closing price due to the absence of trading halts (Ciaian et al., 2016). This makes it difficult for the market to absorb new information efficiently, raising concerns about Bitcoin's reliability as a store of value compared to traditional safe-haven assets like gold.

Most digital currencies can be assessed using simple financial instruments (Liu & Tsyvinski, 2021), require no national backing (Marple, 2021), and lack explicit cash flow (Cheung et al., 2015). Baur et al. (2018) deems that Bitcoin’s excess returns and volatility resemble those of highly speculative assets rather than gold or the U.S. dollar. The scarcity and high stock-to-flow ratio of Bitcoin make it a hedge against political and economic instability. Dyhrberg (2016) finds several similarities between Bitcoin and the gold and dollar markets, suggesting Bitcoin can be classified as a hedge asset between gold and the U.S. dollar.

(3) Other arguments

There is significant criticism from experts who argue that cryptocurrencies are speculative risky bubbles and potential frauds (Cheung et al., 2015; Fry, 2018; Fry & Cheah, 2016). Fry and Cheah (2016) reveal that Bitcoin and Ripple are characterized by negative bubbles. Cheung et al. (2015) identify several short-lived bubbles in the Bitcoin market. Fry (2018) finds evidence of bubbles in Bitcoin and Ethereum and refines a rational bubble model for cryptocurrencies incorporating heavy tails.

The significant volatility of cryptocoins have led to claims that cryptocurrency resembles a digital commodity bubble that could burst anytime (Adrian Cheung, 2015). Many private and centralized cryptocoin projects (Initial Coin Offerings) appear to pose risks of illegal fundraising. According to a Coinpedia survey, several prominent figures have voiced their skepticism: Jamie Dimon (CEO of JP Morgan) suggests Bitcoin is perfect for illicit activities and worse than the Dutch tulip crisis of the 17th century; Jack Bogle (Vanguard founder) compares Bitcoin to a plague, stating that it offers no value; David Gledhill (CIO of DBS) believes Bitcoin is a Ponzi scheme; Howard Marks (co-chairman of Oaktree Capital) calls it an unfounded fad and pyramid scheme; and Michael Novogratz (former Fortress hedge fund manager) says Bitcoin mania is fueled by froth and fraud (Marple, 2021).

2.3.3 Innovative characteristics

It is crucial to make digital transformation possible (European Commission, 2017). As digital currency evolves, it may introduce various innovative characteristics to traditional currency, such as anonymity[1], transparency, traceability[2], hard to tamper, irrevocability (best effort basis)[3], programmability[4], and interoperability (Di Iorio et al., 2024; Hull & Sattath, 2024; Kshetri, 2021). Specifically, Zerocash, Zerocoin, Dash, and Monero are designed to ensure anonymity by keeping personal information confidential. Since the account address is public and visible to anyone in the community, the design of CBDCs would vary significantly in terms of anonymity (Kosse & Mattei, 2022). In addition, the feature of extensive traceability facilitates auditing and compliance with financial regulations.

Interoperable digital currencies can significantly enhance the efficiency of cross-border transactions (Di Iorio et al., 2024). The initial interoperability testing will be

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[1] Asymmetric encryption algorithm ensures transaction security and anonymity, which can protect users' privacy without exposing any real personal information.
[2] The Peer-to-Peer network mechanism is widely employed to enhance the transparency and traceability of digital currency transactions. Transaction and mining information are broadcast to the blockchain network for verification by multiple nodes, and packaged information is stored across the community, making it readily traceable.
[3] The irrevocability is ensured by widely used consensus mechanisms that all nodes in the P2P network maintain the longest legal blockchain, requiring verification by over 51% of the nodes.
[4] In blockchain systems, Distributed Ledger Technology (DLT) can be public or private, such as Bitcoin's UTXO (unspent transaction output) or Hyperledger Fabric as a private distributed ledger within a consortium.

conducted on R3's Corda and private Ethereum platforms. Mizuho Bank, in collaboration with JCB, a major Japanese payment company, will pilot an interoperability system based on blockchain technology (Bank for International Settlements et al.). As digital currency platforms become more interoperable, they may offer alternatives to the SWIFT system and potentially challenge the dominance of the U.S. dollar (Dodgson et al., 2015). Vitalik Buterin (2016), the founder of Ethereum, has proposed three inter-blockchain communication mechanisms—Notary Schemes, Sidechains and Relays, and Hash Time Lock Contracts. To develop seamless interoperable systems, Belchior et al. (2021) provide a comprehensive corpus on interoperability by collecting approximately 400 relevant studies, theoretically demonstrating the potential for seamless interoperability in future digital currencies. Belchior et al. (2021) provide a comprehensive review of blockchain interoperability, exploring the challenges and advancements in achieving seamless communication and functionality across different blockchain networks.

3. Review of private sector digital currency

The work of digital currency has largely focused on private digital currency encompassing Bitcoin, altcoins, and stablecoins. This research has predominantly analyzed digital currencies from the perspective of the micro financial market, focusing on the properties of cryptocurrencies, market dynamics, and their limitations.

3.1 Properties discussion

3.1.1 Price formation

Cryptocurrency prices are influenced by various factors, with supply and demand dynamics as primary drivers. Peng et al. (2023) highlight the supply of Bitcoin is limited and controlled by a cryptographic algorithm, which directly affects its price. Similarly, Ciaian et al. (2016) find price formation of Bitcoin is significantly influenced by both determinants of market forces, such as supply and demand, and Bitcoin's attractiveness. However, Griffin and Shams (2019) take a different perspective by considering the rising competition among alternative digital currencies. They argue that the reduction in the supply of cryptocurrency may not necessarily affect its trading price. Instead, they observe that an increase in the supply of USDT appears to cause short-term rises in Bitcoin prices.

Besides, some analysts focus on the scarcity of cryptocurrency when discussing supply. Although most cryptocurrencies have a certain limited amount individually, there is no scarcity in the whole crypto ecosystem as numerous cryptocurrencies can be launched easily and continuously (Alden, 2020). Further, given the elasticity of the minimum monetary unit, the supply of Bitcoin is not inherently scarce, as it can be subdivided into as many decimal places as necessary. In terms of demand, the large demand for decentralized cryptocurrency in the black market and illegal grey economy, driven by the desire to avoid regulations and legal oversight, is another factor influencing its price.

In addition to the market force of supply and demand, the inherent complexity of the cryptocurrency market also can affect price. Empirical result by Hayes (2017) indicates that mining difficulty, the rate of coin production, and employed algorithms are the three main drivers affecting the value of cryptocurrency. Subsequently, empirical research by Sovbetov (2018) examines the five most common cryptocurrencies (Bitcoin, ETH, Dash, LTC, and Monero) in the ARDL model, and finds the market beta, trading volume, and volatility appear to be the significant determinants of price. Studies show cryptocurrency prices from different exchanges are highly interrelated (Giudici & Abu-Hashish, 2019), with this interdependency affecting each other's prices.

From an external perspective, prior literature documents that the price of digital currencies often exhibits a strong reaction to regulatory changes. Government attitudes also influence cryptocurrency prices, especially when concerns arise about Ponzi or pyramid schemes. For instance, in June 2021, the Chinese government issued the Notice on Further Preventing and Dealing with the Risks of Virtual Currency Trading Hype, declaring all cryptocurrency transactions illegal, which led to a sharp decline in their prices. This was due to the significant number of mining operations in China and the government's crackdown on illegal ICO financing.

In the long run, the price of cryptocurrencies is influenced by collective consensus on their value, ultimately leading to an equilibrium. Haykir and Yagli (2022) discuss that investor sentiment and herding behavior play a significant role in shaping public perception of the intrinsic value and price of cryptocurrencies. For instance, after the outbreak of COVID-19, global quantitative easing led to widespread panic, pushing capital into the cryptocurrency market as investors sought safe-haven assets, which in turn drove up prices (Umar & Gubareva, 2020). However, the intrinsic value of most cryptocurrencies remains ambiguous. Due to the high volatility and fluctuating nature of cryptocurrency markets, traditional fair value measurement approaches may not accurately capture their true worth (Beigman et al., 2023). The European Central Bank (2015) cautions that the speculative nature of Bitcoin and the significant risks it poses to investors.

3.1.2 Price volatility

In examining the price performance over the last decade, volatility is one of the most prominent properties of cryptocurrencies and has caused widespread concern.

The exceptional pricing volatility that has taken place (Katsiampa, 2017) may invalidate the medium-of-exchange function for cryptocurrency. Baek and Elbeck (2015) examine relative volatility using Bitcoin and S&P 500 Index daily return data and find that the Bitcoin market is highly speculative. Similarly, Chaim and Laurini (2018) point out cryptocurrencies exhibit very high unconditional volatility. Additionally, Ji et al. (2019), Katsiampa et al. (2019) further study the volatility spillover effect and connectedness within the cryptocurrency market by examining return and volatility spillovers. Regarding stablecoins, their returns are heteroscedastic compared to stable benchmarks such as major fiat currencies or gold, but generally less volatile than Bitcoin (Hoang & Baur, 2020).

In addition, frequent price fluctuations in cryptocurrency markets create opportunities for arbitrage due to price deviations across different exchanges (Makarov & Schoar, 2020). Before 2017, the arbitrage opportunities in different cryptocurrency exchanges benefited speculators significantly, although these arbitrages are now conducted by robots. This phenomenon contradicts the law of one price for homogeneous assets (Hong Kong Financial Development Council, 2021). In addition to geographic location, arbitrage in cryptocurrencies can occur across different blockchains. Lyons and Viswanath-Natraj (2023) discuss the arbitrage mechanism from the Omni chain (a side chain in the Bitcoin blockchain transferring USDT) to the ERC-20 chain (a side chain in the ETH blockchain transferring USDT). They developed a model to discuss the channels leading to stablecoin premiums and discounts, finding that stablecoins often trade at a premium.

Given the concerns about volatility, uncertainty, and speculation, the literature in this area focuses on price forecasting, which is crucial for investors (Sun et al., 2020). Liquidity plays a significant role in return predictability (Wei, 2018), and Brauneis and Mestel (2018) find a heterogeneous pattern of efficiency, likely related to liquidity and size, with cryptocurrency prices becoming less predictable as liquidity increases. Sun et al. (2020) suggest the Light GBM model is the best method to forecast price trend (falling, or not falling). Lamothe-Fernández et al. (2020) create a new prediction model to forecast Bitcoin's price using deep learning methods. Liu et al. (2021) suggest the cryptocurrency returns can be predicted by markets time-series momentum and investors' attention.

3.1.3 Return and risk

Cryptocurrencies like Bitcoin and Ethereum are prone to extreme price movements that occur more frequently and with greater severity compared to traditional financial assets (Liu & Tsyvinski, 2021). Previous research concentrates on the main drivers of Bitcoin returns. Corbet et al. (2020) examines the impact of macroeconomic news on Bitcoin returns. Liu et al. (2020) provides evidence supporting the significance of momentum in cryptocurrency markets. This research further strengthens the argument that momentum is a primary driver of returns in this asset class. Liu and Tsyvinski (2021) employ various asset pricing models, including the CAPM, Fama-French 3-factor, Carhart 4-factor, Fama-French 5-factor, and Fama-French 6-factor models, to analyze the risk and return of Bitcoin, Ripple, and Ethereum.

Zhang et al. (2018) employ the GARCH model to demonstrate the existence of heavy tails in cryptocurrency returns, which display strong volatility clustering and leverage effects. Gkillas and Katsiampa (2018) employ extreme value theory to investigate the tail behavior of returns of the five largest cryptocurrencies. But tail independence suggests a safe-haven property of cryptocurrencies, as they are not exposed to the financial contagion of the stock market (Feng et al., 2018a).

According to modern portfolio theory (Markowitz, 1952), portfolio diversification strategies can reduce the risk associated with individual assets. Investors are particularly concerned with the risks of their investments and the role of cryptocurrencies in diversification and hedging purposes (Feng et al., 2018a). some research asserts that cryptocurrency possess safe-haven properties, allowing them to hedge against risks in other assets, such as stocks and currencies (Antonakakis et al., 2019). Briere et al. (2015) analyze Bitcoin's performance from 2010 to 2013 and finds that its correlation with traditional assets such as stocks, bonds, and commodities was remarkably low during this period. Wang et al. (2020) study the diversifier, hedge, and safe haven properties of USD-pegged and gold-pegged stablecoins compared to traditional cryptocurrencies. Guesmi et al. (2018) demonstrate that shorting Bitcoin can hedge risks in various financial markets. Additionally, including even a small amount of Bitcoin in a diversified portfolio can significantly improve the risk-return profile.

However, Su et al. (2020) note that although it is not a reliable hedge in all scenarios, Bitcoin can act as a safe-haven asset during periods of geopolitical uncertainty. Aysan et al. (2019) show that Bitcoin can be considered as a hedging tool against global geopolitical risks. Mariana et al. (2021) show that Bitcoin and Ethereum are suitable as short-term safe-havens during the COVID-19 pandemic. Feng et al. (2018a) suggest that while cryptocurrencies can act as diversifiers similar to gold, they are not as effective for tail-hedging.

3.2 Cryptocurrency market analysis

The cryptocurrency market is gradually becoming more complex, exhibiting some similarities to the stock market while maintaining several distinct differences.

3.2.1 Market efficiency

Efficient Market Theory (Fama, 1965) has been widely discussed in the context of cryptocurrencies since 2016. With the increasing popularity of cryptocurrencies and the development of crypto markets, numerous studies have examined weak market efficiency. Urquhart (2016) firstly analyses the efficiency in the Bitcoin market, and finds that Bitcoin does not follow the Efficient Market Hypothesis and exhibits signs of inefficiency, particularly in the short term.Tiwari et al. (2018) review informational efficiency from 18 July 2010 to 16 June 2017, finding that Bitcoin is generally efficient except during April-August 2013 and August-November 2016. In this line, Jiang et al. (2017) affirm there is a presence of long memory in the Bitcoin market. Nadarajah and Chu (2017) highlight the weak efficiency of Bitcoin using power transformations of daily returns.

Vidal-Tomása and Ibañez (2018) examine the semi-strong efficiency of Bitcoin in the Mt.Gox and Bitstamp markets. They conclude that Bitcoin returns respond quickly to negative events in both market samples, but it is insufficient to affirm that the Bitcoin market is completely efficient due to the absence of a clear response to positive news. The empirical results further contend that Bitcoin does not respond to international monetary policy, indicating that central banks are unable to control the Bitcoin market, unlike the situation in stock markets (Brenner et al., 2009; Pennings et al., 2015).

However, the literature shows a high correlation within the cryptocurrency market, but isolated from other traded assets. Corbet et al. (2018) investigate the relationships among alternative cryptocurrencies such as Bitcoin, Litecoin and Ripple, revealing a strong interconnectedness among them. Their findings suggest that cryptocurrencies are largely isolated from traditional financial markets. Ciaian et al. (2016) analyze the relationship between Bitcoin and sixteen alternative coin prices, finding that they are indeed interdependent.

3.2.2 Exchange rate

Similar to existing currency systems, cryptocurrencies have formed an exchange system, with their relative values to each other serving as exchange rates that represent the relationships among cryptocurrencies to a certain extent.

Hui et al. (2020) further propose a standard flexible-price rate monetary model to investigate Bitcoin’s characteristics as a currency, concluding that fluctuations in Bitcoin’s exchange rate are mainly driven by demand. De Blasis et al. (2023) examine how the design and collateralization of stablecoins affect their stability, and point out that under-collateralized stablecoins are particularly vulnerable to speculative attacks. Lyons and Viswanath-Natraj (2023) link stablecoins to fixed exchange rate regimes and analyze the mechanisms driving deviations from a peg in both directions. Using the standard flexible-price rate monetary model, Hui et al. (2020) derive a model of Bitcoin's exchange rate dynamics to show that the Bitcoin exchange rate exhibits characteristics of commodity currencies with crash risk.

Mensi et al. (2021) investigate the cross-correlations among major cryptocurrencies using high-frequency data and nonlinear Granger causality. Their findings highlight significant interconnectedness and co-movements among cryptocurrencies. They use intraday price data from six cryptocurrencies, including Bitcoin, Ethereum, Litecoin, DASH, Ripple, and Monero, and analyze how these correlations evolve over time.

3.2.3 Transaction platforms

The cryptocurrency market is characterized by both centralized and decentralized platforms, but truly decentralized products are limited. Currently, there are nearly 400 crypto exchanges worldwide, divided into Centralized Exchanges (CEXes), Decentralized Exchanges (DEXes), and Hybrid-decentralized Exchanges (HEXes) (Hägele, 2024).

CEXes, like Mt. Gox, which suffered a major hack in 2014, require identity verification, compromising the anonymity of cryptocurrencies and posing security risks. This practice may violate the anonymous design of cryptocurrency, and the asset custody business faces security risks such as hacker attacks, insider threats, or founders absconding with funds. Some incidents in CEXes can burst cryptocurrency bubbles. Approximately 850,000 Bitcoins, worth around $450 million at the time, were stolen from the Mt. Gox exchange in 2014, causing Bitcoin's price to crash to $0.01 (Cheung et al., 2015). Similarly, Bitfinex lost $65 million in a hacker attack in 2016; about $524 million NEM in Coincheck centralized exchange was stolen in 2018.

In contrast, DEXes, guided by the principles of Decentralized Finance (DeFi), use the Automated Market Maker (AMM) mechanism for trading[1] (Makarov & Schoar, 2022), offering better privacy and security. DEXes obtain liquidity solely from participants and share fees with capital providers, called makers, who sell digital assets into the liquidity pool. Participants, including seller and buyer, cannot set their desired prices. The buyer's counterparty is no longer a person but a smart contract. Based on the AMM mechanism, anyone can be a maker of DEXes and earn a certain interest (e.g. 0.3%) on the tokens they provided. Investors trade with the tokens in the liquidity pool rather than buying from a specific seller (Mohan, 2022). While DEXes ensure assets are managed by smart contracts, enhancing security, technical barriers and slower transaction speeds remain challenges. When a DEX is set up on a specific blockchain, transactions can only use tokens produced by that blockchain and can only trade cryptocurrencies which are connected to that blockchain. For instance, Uniswap on Ethereum uses ERC20 tokens, while Justswap on TRON uses TRX. Traders on Ethereum-based DEXes need to use WETH (wrapped Ether) for trading other ERC20 tokens. Bitcoin, lacking smart contract functionality, cannot be traded on these platforms. This constraint reduces the interoperability of DEXes compared to centralized exchanges, which can handle a broader range of assets.

In addition, transactions in HEXes are executed on-chain but settled off-chain. However, this hybrid mode remains underdeveloped and presents significant security risks, comparable to those associated with DEXes. 3.2.4 Legality and regulation

The cryptocurrency market suffers from a weak legal framework (Bouri et al., 2019). The innovative nature of cryptocurrencies, which can bypass traditional banking

[1] The trading price is calculated by AMM model: X * Y =K, where X is the amount of one token in the liquidity pool, Y is the price, and K is a fixed constant.

systems, poses significant challenges for regulators in establishing clear taxation frameworks. This lack of clarity complicates the understanding of tax obligations for individuals and businesses dealing in digital currencies (Shestak et al., 2021). The challenge lies in classifying crypto assets—whether as untaxed money, debt, or equity. As a result, establishing clear taxation frameworks remains a complex task.

While cryptocurrencies have legitimate uses in many areas, Foley et al. (2019) express concern over the ongoing association of cryptocurrencies with illegal activities, such as money laundering and illicit trade, suggesting that this issue requires careful consideration from policymakers and regulators. Despite some jurisdictions efforts in implementing comprehensive regulations, the lack of uniformity and consistent enforcement effectiveness remains a major challenge. For example, Malta’s proactive regulatory framework has been undermined by enforcement gaps.

At the beginning of the decentralized cryptocurrency era, Bitcoin was unaffected by monetary policy news, highlighting the absence of any control (Vidal-Tomása & Ibañez, 2018). Grinberg (2012) analyses the relationship between Bitcoin and central bank's currency issuance rights, security law, and anti-money laundering law. The New York State Virtual Currency Regulatory Framework (Bitlicenses), issued in 2014, is a relatively comprehensive financial regulation for virtual currency. The anonymous nature of currency raises concerns regarding compliance with anti-money laundering and counter-terrorism financing requirements. Favarel-Garrigues et al. (2011) address the risks posed by anonymous digital currencies and the challenges they present to AML and CFT efforts.

Much attention has been paid to initial coin offerings (ICOs), which involve issuing digital tokens to raise money. Howell et al. (2020) provide a detailed examination of how ICOs function as a financing tool, with parallels to initial public offerings, venture capital, and presale crowdfunding. However, ICOs are a controversial means of raising funds to avoid regulation, with features that may also attract illegal activities, such as money laundering, drug trafficking, smuggling, and weapons procurement.

3.3 Current limitations

The practice of cryptocurrency has revealed a series of problems and technical bottlenecks. While many of these issues will be gradually overcome, some difficulties will significantly restrict the future development of the private digital currency industry.

3.3.1 The blockchain trilemma

It is an urgent matter for private sector digital currency to achieve convenience in frequent daily payments. The blockchain trilemma, often referred to as the Impossible Trinity in the context of blockchain technology, suggests that a blockchain system cannot simultaneously achieve full decentralization, high scalability, and strong security. Cryptocurrencies can only achieve two out of the three aspects of the impossible trinity (Buterin, 2016).

First, the Trilemma Claims mentioned above, including three aspects of decentralized, security, and scalability. This issue is unlikely to be resolved in the short term without significant technical breakthroughs in areas such as consensus algorithms or Layer 2 solutions, which could radically improve scalability and efficiency (Leonardos et al., 2020). Bitcoin's scalability remains a critical issue. Alvarez et al. (2023) point out that the network’s capacity to process transactions—typically around 7 transactions per second—is insufficient to handle large volumes efficiently, often resulting in congestion and delays.

Second, there is the issue of data privacy. In blockchain systems, while personal information may be pseudonymous, all transaction data is publicly accessible and permanently recorded on the ledger. This creates a tension between transparency and privacy, as individuals who value privacy may be reluctant to use a system where their transaction history, though not directly linked to their identity, is publicly visible (Conti et al., 2018). The adoption of such systems may thus be slow, particularly among those who prioritize privacy. It will take time for citizens to adapt or accept this change brought by new technology, and it the process may be slow, especially for individuals who prioritize freedom and privacy.

Third, there is the limitation of value instability and limited payment scenarios. Generally, it is challenging for a cryptocurrency to function effectively as a medium of exchange if it does not have legal tender status. This lack of legal recognition limits its usability in everyday payment scenarios and contributes to value volatility, as it is primarily used for speculative purposes rather than for stable, widespread transactions (Alvarez et al., 2023). Currently, there is a lack of usability for cryptocurrencies. Cryptocurrencies will continue to experience value instability and will be difficult to use widely in various daily payment scenarios in the real world.

3.3.2 Treat of quantum computing

There is a growing concern about whether quantum computing or quantum satellite technology will break the encryption and the security of cryptocurrencies. If a quantum computer breaks the encryption, not only cryptocurrency but also all other accounts may no longer be safe. Thus, quantum computing will make CBDC more necessary instead and push its progress forward.

Cryptocurrency's security mainly relies on three components: encryption, irrevocability, and traceability. Even when stolen, the irrevocable blockchain technology and traceable distributed ledger technology can continue to guarantee the security of cryptocurrency, as quantum computing can only decipher the password but cannot delete transaction records if the ledger is sufficiently dispersed. In other words, traceability will act as a deterrent to the hacker. Conversely, if a country does not have CBDC, authorities cannot track the whereabouts of stolen electronic currency, because it can be changed for paper money and remain untraceable.

Additionally, quantum computing will make cryptocurrencies safer. So far, quantum computing has a very high technical threshold for the public, and no one except the state will own a quantum computer in the near future. Criminals may fear that their account information (balance, transfer records, etc.) will be accessed by the police through quantum computing more than they fear theft.

Therefore, if quantum computing eliminates the money-laundering function of cryptocurrencies, their remaining functions will be investment and payment. In the payment field, cryptocurrencies are generally weak competitors compared to CBDCs. However, cryptocurrencies could improve the transparency of fiat currency issuance, elimination, and circulation, which might be uncomfortable for states.

From a broader perspective, with the development of quantum computing, more complex encryption technologies will likely appear in the future, such as quantum encryption or biological encryption. In a society where quantum computing is prevalent, it is possible that all systems will require blockchain technology.

3.3.3 Lack of transaction scenarios

Despite global discussions and the growing interest in cryptocurrencies, Bitcoin's actual adoption rate remains relatively low (Feng et al., 2018b). A prime example is

Malta, which has passed laws[1] to establish a comprehensive regulatory framework to create a favorable environment and regulatory measures for cryptocurrency. However, it failed. This limited adoption can be attributed to several factors, including legal uncertainties and an underdeveloped payment infrastructure. And the high transaction fees and slow confirmation speeds, particularly during periods of network congestion caused by limited block size and fluctuating miner fees, further restrict Bitcoin's suitability for high-frequency, low-value transactions (Khan et al., 2021). Furthermore, misconceptions about Bitcoin's usability and technical barriers have hindered its acceptance as a mainstream currency. The legal status of Bitcoin varies significantly across different countries, and the regulatory environment remains uncertain, posing substantial risks to its broader application (van der Linden & Shirazi, 2023). For instance, while some countries like Malta have attempted to establish comprehensive regulatory frameworks to support cryptocurrency development, inconsistencies and enforcement challenges have hampered these efforts. Such regulatory ambiguity can deter institutional investors and limit Bitcoin's integration into regulated financial systems (Chokor & Alfieri, 2021).

The global acceptance of digital currencies faces numerous obstacles beyond technical and regulatory challenges. Although many private cryptocurrencies are striving to expand their use cases, creating a suitable operational environment is a complex endeavor. Such an environment is more likely to emerge in regions with robust material resources, well-developed social welfare systems, and minimal wealth disparity, rather than in underdeveloped areas or countries experiencing severe inflation. Achieving widespread acceptance requires not only technological advancements but also socio-economic stability and comprehensive regulatory support (Shahzad et al., 2024).

Given these complexities, it remains uncertain whether a fully decentralized cryptocurrency could function as a viable form of currency in a future specialized economic society, akin to a "Bitcoin society and economy." Current social conditions suggest that a more pragmatic approach would involve integrating digital currencies into existing financial systems while maintaining a degree of decentralization (Harvey & Rabetti, 2024). Such a hybrid model, balancing innovation with regulatory compliance and financial stability, appears to be more likely to gain broad acceptance.

4. **Review of central bank digital currency**

The work of digital currency to date largely is focused on Bitcoin but there are some other topics that reflect interest. In response to the experiences and limitations of private digital currencies, the role of central bank digital currency is a fast-developing branch of monetary economics (Raskin & Yermack, 2018). The existing economic frameworks of private digital currencies, including cryptocoins and stablecoins, have provided valuable insights for the study of CBDC. This section highlights the growing body of literature on digital currency envisioned by sovereign states, commonly referred to as CBDC. It provides an overview of its primary designs and addresses the concerns regarding potential impacts on existing financial systems.

4.1 Top designs of CBDC

4.1.1 Payment motive

Generally, cash and clearing accounts of financial institutions represent two forms of central bank's monetary liability (Christian & Henry, 2019). Based on this framework, the CBDC would introduce two types of CBDC, retail CBDC and wholesale CBDC. Retail CBDCs are intended for general public use, while wholesale CBDCs are designed for financial institutions (Auer et al., 2023; Bech & Garratt, 2017). Basically, the design of retail CBDC must be able to cope with the needs of highly concurrent but low-price payment. Alternatively, compared with the retail CBDC, the wholesale variant may have a relatively mild influence on the financial system due to the restricted access only for financial institutions that look broadly similar to the way opening clearing accounts with the central bank works. The countries and regions considering wholesale CBDC are Singapore (project of Ubin), Hong Kong, Thailand, Japan, Canada (projects of Jasper), France, etc. The Canada, Singapore, and UK proposal is jointly envisaging an unified international CBDC, it is similar to Libra but composed of multiple central banks (Bank of Canada et al., 2018).

4.1.2 Interest rate

Another concern is whether a CBDC should bear interest. Generally, an interest-bearing CBDC with a high rate could negatively affect bank lending and create competition between central banks and financial intermediaries. Wilkins (2022) suggests that an interest-bearing CBDC could help balance the trade-off between bank intermediation and the social value of holding cash. In contrast, China's e-CNY is designed as a non-interest-bearing currency to avoid displacing bank deposits (Mu, 2020). However, some studies show that an interest-bearing CBDC may improve bank intermediation, particularly in markets where deposit competition is not perfect. In such cases, a moderate interest rate on CBDCs could increase both bank deposits and lending, but it could cause a disintermediation when the interest rate is too high (Andolfatto, 2021; Chiu et al., 2019; Chiu et al., 2023). In a working paper released by Bank of England, John and Kumhof (2016) define CBDC as a universally accessible and interest-bearing central bank liability that competes with bank deposits as a medium of exchange. Additionally, Kim and Kwon (2023) argue that the issuance of a CBDC could allow central banks to implement negative interest rates, effectively overcoming the zero-lower bound constraint and expanding the scope of monetary policy.

4.1.3 Operational mechanism

The operational mechanism of CBDC is also an open question for current research. There are two designs named as “one-tier operational mechanism” and “two-tier operational mechanism” (refer to Figure 2.3 and 2.4).

Researchers consider that adopting the one-tier operational system that the central bank issues digital currency to the general public directly may lead to competition between the central bank and commercial banks. In this case, it would probably raise the financing cost to commercial banks, and further influence the entire economy to some extent. Chen and Siklos (2022) consider CBDCs may weaken the profitability of commercial banks and affecting the transmission of monetary policy.

Alternatively, the mainstream design is the two-tier operate/delivery/distribution system. In this two-tier banking system, CBDC is delivered to financial institutions first, then be distributed to individuals and non-financial institutions only through them. This design would operate alongside the current economic infrastructures, legal supervision system, and monetary distribution system, and it is beneficial for economic stability.

The projects of “digital dollar” and “digital Chinese Yuan” tend to choose the two-tier delivery system to avoid financial disintermediation and to make the most out of the existing financial system. Similar to the projects of Digital Dollar and digital Chinese Yuan that adopt a two-tier operational system, Danezis and Meiklejohn (2015) came up with a design called the RSCoin system that is trying to achieve an extensible encrypted digital currency controlled by the central bank but not limited to blockchain technology.

Figure 2.3 One-tier CBDC delivery banking system

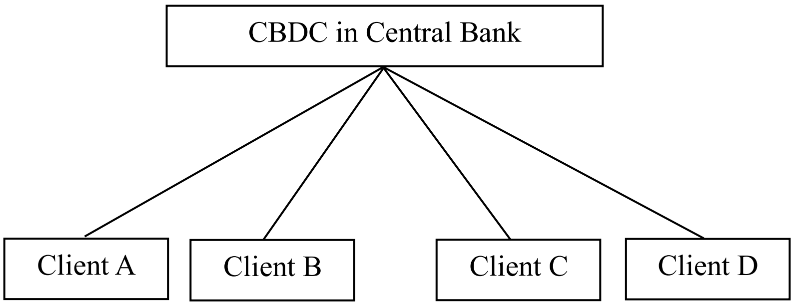
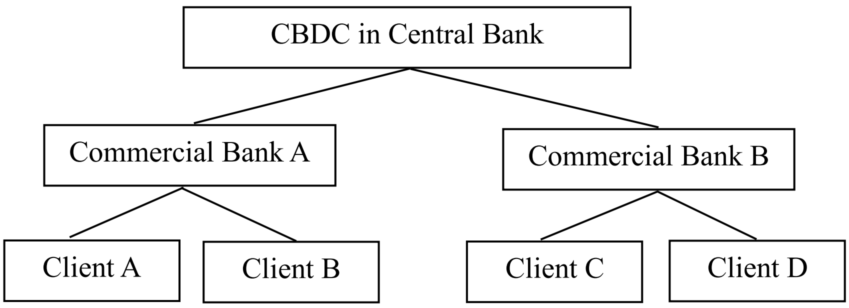


Figure 2.4 Two-tier CBDC delivery banking system



4.2 Potential macro-financial impacts

4.2.1 Reshaping the payment system

The emergence of digital currency would have far-reaching effects on current payment systems. Initially, the CBDC could reinforce the resilience of payment systems. The Riksbank is investigating whether an e-krona would provide the public with continued access to central bank money and increase the resilience of the payment system (Sveriges Riksbank, 2017, 2018, 2020). On a related note, CBDC could reduce the concentration of liquidity and credit risk in payment systems (Jun & Yeo, 2021).With this concern, Andolfatto (2024) suggests that central banks should leverage these technological advancements to improve their payment systems rather than focusing solely on developing blockchain-based currencies.

Another topical issue is the impact on cross-border payments. In the expectation of wholesale CBDC, the original payment system based on account bookkeeping would transform into the form of digitized tokens to significantly improve the transparency and efficiency of cross-border payments (Auer et al., 2023). Using distributed ledger technology will improve the efficiency of the payment system (wholesale CBDC), especially cross-border payment. Project Jasper, a collaborative initiative between the public and private sectors, examines how distributed ledger technology (DLT) can reshape wholesale payment systems and securities settlement processes, potentially transforming the future of Canada's financial market infrastructure (Bank of Canada, 2018).

Besides, there is a concern that the thriving CBDC may cause an international spillover effect, as well as challenging the U.S. dollar dominance. If a strong CBDC were to be globally adopted, it could indeed become a more stable and trusted alternative in countries experiencing severe inflation or where the public has lost trust in domestic currencies (Georgieva, 2022).

4.2.2 Concerns of Deposit Crowding-Out

The crowding out effect of CBDC means when a central bank delivers CBDC (the liability of the central bank) to the public directly, it goes round commercial banks and the deposits in commercial banks are exchanged for CBDC (Bian et al., 2021). As CBDC is typically the central bank's liability to the public, the banknote deposited in commercial banks would flow into the digital wallet belonging to the central bank once individuals decide to exchange their deposits for CBDC.

Scholars are concerned that introducing CBDC could encourage depositor runs (Agur et al., 2022; Wilkins, 2022), because central banks will become competitors for other banks as a deposit monopolist (Fernández-Villaverde et al., 2021), and threaten the stability of the financial system (Brunnermeier & Niepelt, 2019). By offering a digital alternative to physical cash and bank deposits, CBDCs could meet the demand for safe, short-term assets (Wronka, 2023). Abad et al. (2023) analyze the potential impact of CBDC on the operational framework of monetary policy, particularly focusing on how it could lead to a decrease in bank deposits.

There are several schemes trying to deal with this problem. First, to control the transfer authority of CBDC by forbidding the transfer of CBDC from commercial bank accounts to central banks instantly (Banks of England, Sweden, Norway). Second, to specify the amount of CBDC that citizens can hold, such as setting a superior limit (Bank of Denmark), but how to set the specific boundary remains to be discussed. Furthermore, to set a flexible interest rate for CBDC. For instance, when a person holds less than a certain amount the interest rate is positive, while over that it turns into a negative one (European Central Bank).

4.2.3 Enhancing traditional monetary policy

Much research on the topic of CBDC is based on the perspective of e-money in essence. However, CBDC is not only a simple innovation of electronation but also the evolution of currency itself. In this context, some argue that the technology behind digital currency may give authorities more power and control over monetary policy than ever before (Raskin & Yermack, 2018).

CBDCs could affect monetary policy implementation (Abad et al., 2023; Lukonga, 2023). These effects could include changes in money velocity, disintermediation of bank deposits, volatility in bank reserves, and shifts in capital flows (Lukonga, 2023). Since 1996, BIS has been discussing the influence of electronic currencies on monetary policy and payment systems. These discussions focus on the aspects of accelerating the transfer among financial assets, promoting the efficiency of interbank operations, reducing the monetary base, amplifying the monetary multiplier, and strengthening the monetary transmission mechanism (Bank for International Settlements, 2000, 2004). CBDCs can positively influence monetary policy transmission and financial stability by altering the competitive dynamics within the banking sector (Bank for International Settlements and the World Bank, 2022).

Wu and Zhang (2024) examine the implications of CBDCs for monetary policy. They explain that replacing physical banknotes with CBDCs could reduce M0, bank deposit reserves, and the monetary base, while potentially increasing the currency multiplier. Chen and Siklos (2023) provide evidence on how the introduction of retail CBDCs could increase currency substitution in some economies, impacting the effectiveness of domestic monetary policies. CBDCs might reduce risks related to financial crises by providing a safer and more efficient payment system, as well as by improving the central bank's ability to implement monetary policy (Tercero-Lucas, 2023).

4.2.4 Potential macroeconomic impacts

CBDC that completely replaces physical cash may better deal with recession, unemployment, and deflation by imposing negative interest rates (Rogoff, 2016). Raskin and Yermack (2018) argue that CBDC raises a revival attention on classical monetary economics and would represent the financial socialism that narrows the relationship between the public and central banks and gives states a greater control over monetary policy than ever before as the interest rate could be negative. Lukonga (2023) notes that CBDCs could potentially increase financial stability by reducing financial frictions in the deposit market, promoting financial inclusion, and improving the transmission of monetary policy.

The privacy design of CBDCs plays a crucial role in combating money laundering, tax evasion, and other illicit activities (Z. Wang, 2023). Central banks are not expected to issue a fully anonymous digital currency, as designing a CBDC that balances anonymity with regulatory requirements while ensuring user trust is highly complex.

By avoiding the traditional liquidity trap, central banks can achieve better economic outcomes through more adaptive monetary policy frameworks (Cochrane, 2017). In contrast, the excessive use of cryptocurrency will weaken the transmission of existing monetary policy and limit the central bank's role of lender-of-last-resort (Das et al., 2023). Bech and Garratt (2017) believe CBDC could facilitate the systematic and transparent conduct of monetary policy as a practically costless medium of exchange. There are two more points worth considering. One is CBDC will enhance the central bank's ability to obtain data related to monetary policy regulation accurately. Wu and Zhang (2024) highlights that the introduction of CBDCs can disrupt traditional monetary policy channels, such as the interest rate and bank lending channels. The other one is the characteristics of transparency and hard to tamper with CBDC will help the central bank to get an accurate and real feedback of monetary policy implementation.

At the same time, some doubt that it would be possible not alter the basic mechanics of monetary policy implementation. To support this argument in a way, Woodford (1998); Woodford (2000) analyses monetary policy in the cashless world. Ali et al. (2014) earlier assess the challenge that private digital money may pose to the Bank of England's monetary and financial stability. He believes that small-scale digital money will not have a substantial impact on monetary policy.

4.3 Operational challenges

4.3.1 Technical security

One of the most significant operational challenges for CBDC is technical security, particularly the privacy protection. Many regions often lack the advanced technological infrastructure necessary for CBDCs (Alora et al., 2024). This makes it difficult to ensure user data security and maintain privacy with sophisticated encryption.

4.3.2 Legal frameworks

Another critical challenge is the inadequacy of existing regulatory and legal frameworks to handle the complexities and risks associated with CBDCs (Alora et al., 2024; Claessens et al., 2024).

4.3.3 International cooperation

Interoperability is essential to facilitate seamless cross-border transactions and to integrate CBDCs into the global financial system. However, this is a complex issue that requires the establishment of unified technical standards and protocols (Alora et al., 2024).

4.3.4 High operational cost

Further consideration is required as to whether digital currency will be a nightmare or a Pareto optimality scheme for small countries. Cryptocurrency has shown the technical feasibility of issuing a CBDC (Kumhof & Noone, 2021). However, maintaining this huge blockchain system running CBDC will be very expensive and complex for a small country. Therefore, small economies or countries with high inflation may not need to develop their own systems but can choose to adopt a reliable CBDC or cryptocurrency. As a result, countries that fall behind in the digital race may find their currency marginalized in the new economy driven by digital currency.

5. Conclusion

In this final section, we conclude the mainstream of digital currency research from the perspective of its evolution stages, highlight some neglected interests in the system, and highlight potential research gaps for further research.

5.1 Current research mainstream

Researches basically study digital currency from the perspective of the macroscopic economics issue for CBDC (Chiu et al., 2019), and that of microcosmic finance for cryptocurrency. In the pre-Bitcoin era, the theme of cryptocurrency was primarily a branch of computer science. Fragmentary studies touch on its function of payment, but basically from a technical point of view. Before CBDCs were taken seriously (during the period between 2008 to 2014), discussions around cryptocurrency predominantly represented digital currency, with a major focus on Bitcoin. Initially, numerous whitepapers directed academia's attention to various innovative ideas. However, as negative events in the cryptocurrency market became frequent, observers and scholars grew concerned about the risks and limitations specific to private digital currencies. Generally, the majority of research regarded digital currency largely as a financial derivative to a large extent.

Furthermore, previous research concludes that digital currencies can be categorized from various dimensions: encrypted versus unencrypted, centralized versus decentralized (pertaining to anonymity), regulated versus unregulated, token-based versus account-based, and private sector digital currency (cryptocurrencies) versus public sector digital currency (CBDCs and central bank cryptocurrencies). From our perspective, digital currency is a real electronic currency, endorsed by authority, embodying all general characteristics of fiat money, and intended for daily payment and settlement use. Conversely, conventional electronic currency is merely an electronic token issued by financial institutions.

In contrast to the perspective of micro finance, since 2014, the body of literature on the macroeconomics of CBDC is increasing gradually, currently covering conceptual research, proofs-of-concept, experiments, etc. The sudden arrival of COVID-19 in 2020 is driving digitalization of payment to new heights. In the same year, the joint report issued by seven major central banks notes that the public digital currency is developing as a significant part in the field of digital currency (Bank for International Settlements et al., 2020).

5.2 Further themes reflecting interest

In addition to the mainstream research themes mentioned in the survey, we find that several other topics in the system that also reflect interest. These include cryptocurrency's market microstructure (Dyhrberg et al., 2018; Koutmos, 2018b). Additionally, the study of cryptocurrency market contagion effects linked to volatility and liquidity (Antonakakis et al., 2019) is important for understanding systemic risk in the broader financial ecosystem. Furthermore, the development of CBDC equilibrium models (Mishra & Prasad, 2024) and the exploration of spillover effects among digital currencies (Koutmos, 2018b) are also critical, as these issues will shape future monetary policy and regulatory frameworks. Addressing these areas is essential for comprehending the evolving impact of digital currencies on global financial stability and integration.

CHAPTER THREE ESSAY TWO

Currency in the Digital Age: How CBDCs Can Reshape Currency Invoicing Power

Abstract

This chapter explores the potential influence of CBDCs' development on currency's invoicing capability in international trade. Based on the theories of exchange rate pass-through and currency pricing, the study constructs a model of currency choice for invoicing, including CBDC announcement shock for moderating effect. Utilizing the bilateral trading data of the top 50 countries with their 186 global trading partners from 2005 to 2022, the findings indicate that the development of producer country's CBDC strengthens the pass-through of exchange rate into consumer prices, suggesting an enhanced currency invoicing power, and this effect is more pronounced in CBDC pilot countries. Mechanism analyses reveal that the currency invoicing power improved through reducing exchange rate volatility and increasing currency liquidity. Our research provides insights for policymakers that fostering the development of CBDCs could promote the use of national currencies in international trade, as well as improving internationalization of currencies.

Key words: central bank digital currency, currency invoicing, exchange rate pass-through, exchange rate volatility, foreign-exchange liquidity

1. Introduction

The dominant role of the U.S. dollar has been a long-term trend. The introduction of the Euro and the economic rise—first of Japan and now of China—have not changed the 'privilege' of the U.S. dollar (Reuters, 2024). Despite the collapse of the Bretton Woods system, the U.S. dollar remains the dominant reserve currency, accounting for approximately on one side of 88% of all trades (BIS, 2024) and 60% of global official foreign exchange reserves as of 2024 (Arslanalp et al., 2024). The dominance in international reserves, trade and financing has implications for corporate risk management as well as the international transmission of shocks (Amiti et al., 2022). This dominant role as the major invoicing currency has led to its sustained appreciation, which has diminished the relative purchasing power of other nations and contributed to a decline in global trade (Gopinath et al., 2020). While the U.S. dollar remains the dominant vehicle currency (refer to Figure 3.1), its share in global foreign exchange reserves has declined from 72% in 2001 to 59% in 2023 (refer to Figure 3.2). The decline in reserves reflects potential challenges to the U.S. dollar's dominance, although the decrease in U.S. dollar reserves has not extended to its use in international banking, currency trading, or derivatives.

There is an increasing focus among countries on developing their national currencies as alternatives to U.S. dollar for invoicing purposes (Liu & Papa, 2022). In June 2024, Saudi Arabia announced its decision not to renew the longstanding petrodollar agreement with the United States. Instead, it is exploring the use of mBridge, a CBDC cross-border payment platform led by the Bank for International Settlements, to price oil in currencies other than the U.S. dollar. Additionally, the BRICS countries are exploring the use of their digital currencies or a new BRICS digital currency for international settlements, which could challenge the dominance of the U.S. dollar in the future. As of May 2024, governments have increasingly engaged in the research and development of CBDCs, with around 134 countries and currency unions, representing 98% of global GDP, are exploring a CBDC (Atlantic council, 2024) (refer to Figure 3). With the development of CBDCs, cross-border CBDC payment platforms are emerging in various countries. As CBDCs are issued by central banks and thus have a profound influence on financial systems, potentially reshaping the way money is created, distributed, and used globally. Innovative digital financial technologies applied to currency have enabled fast payments, reshaping retail payment and settlement systems globally (Guo & Dan, 2023). Therefore, a critical question arises: can CBDCs effectively enhance the attractiveness of a country's currency and thereby impact currency diversification?

Figure 3.1 The role of U.S. Dollar in foreign exchange market

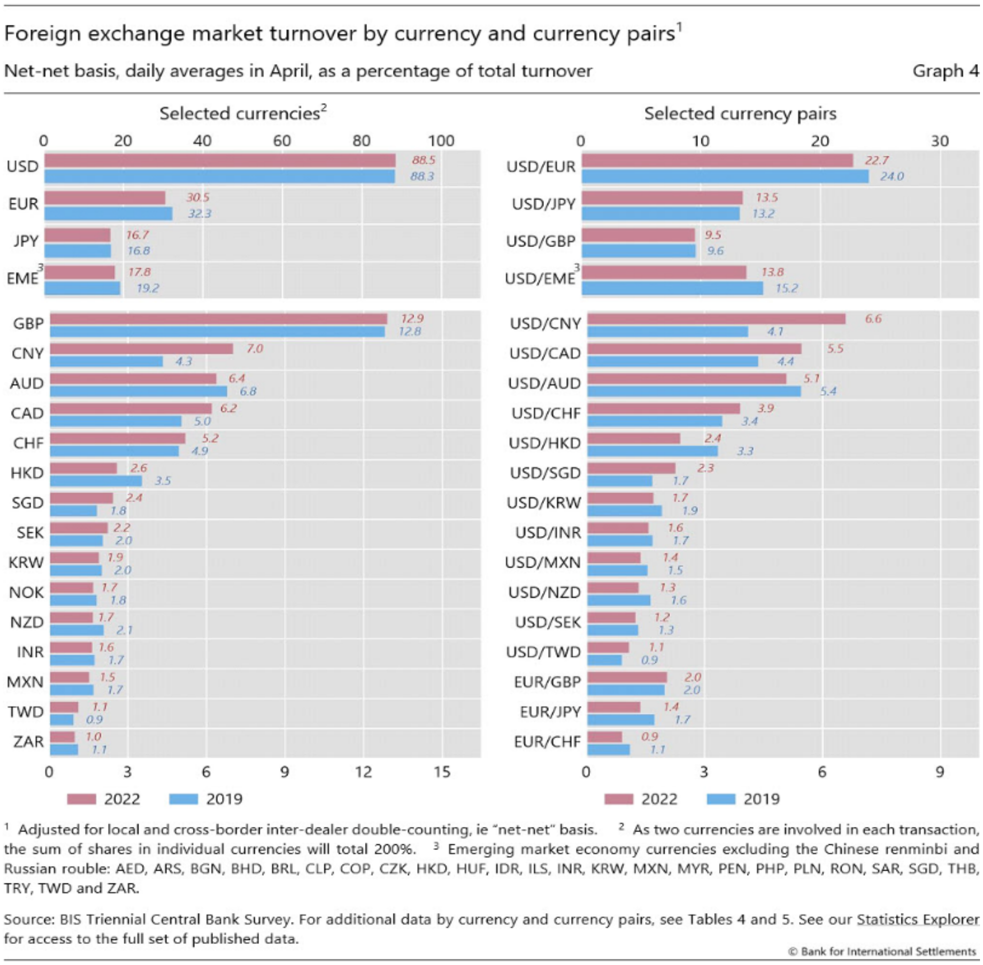


Figure 3.1 shows that USD remains the dominance vehicle currency. In 2022, the U.S. dollar was involved in 88% of all trades (unchanged from 2019). The euro's share declined slightly to 30% (down from 32% in 2019). The Japanese yen and the pound held steady at 17% and 13%, respectively. The Chinese yuan's share increased to 7%, making it the fifth most traded currency in 2022 (up from eighth place in 2019 when it accounted for 4% of trades). (Source: BIS triennial survey 2022)

Figure 3.2 Challenge to the U.S. Dollar's dominance

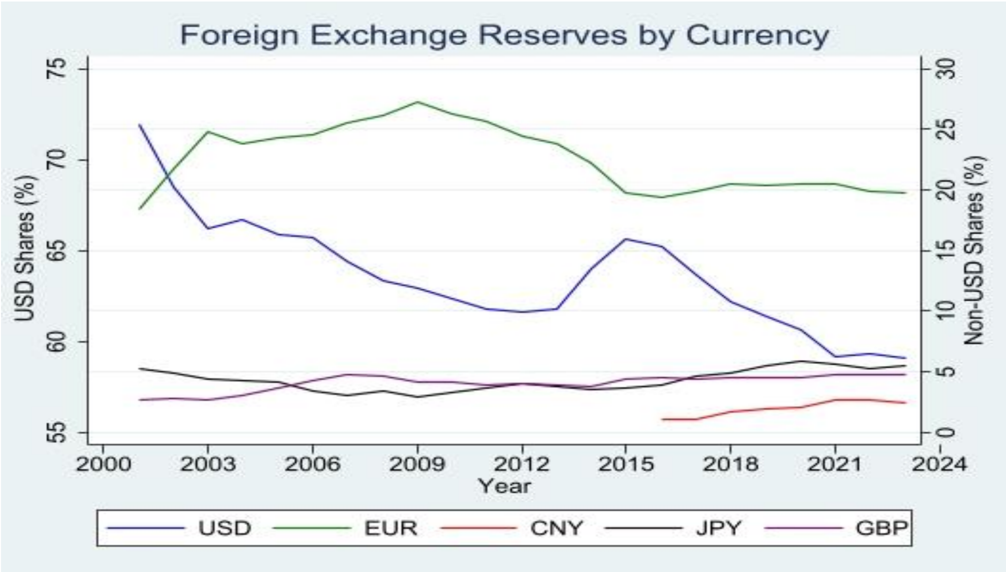


Figure 3.2 illustrates the currency composition (share) of the top five global economies' currencies in global foreign exchange reserves. The five currencies included are the U.S. dollar (USD), Euro (EUR), Chinese Yuan (CNY), Japanese yen (JPY), and U.K. pound sterling (GBP). The dollar's share has decreased from 72% in 2001 to 59% in 2023, showing the challenge to the U.S. Dollar's Dominance. The euro's share has remained stable, while the CNY has been increasing steadily since 2016. (Source: IMF)

Figure 3.3 Distribution of CBDC's progress globally

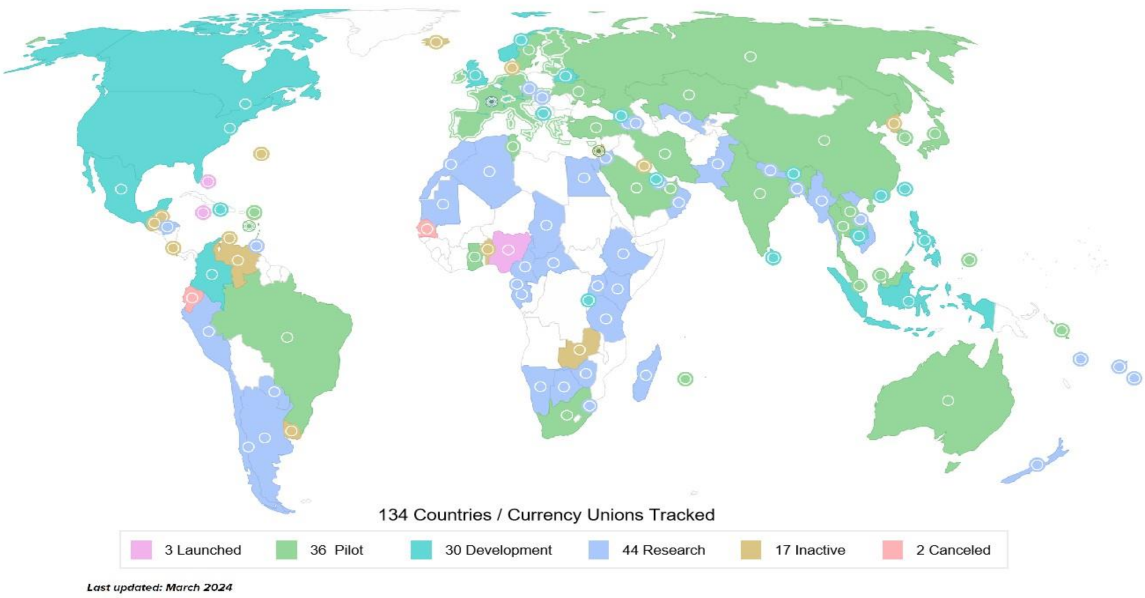


Figure 3.3 illustrates the distribution of global CBDCs development. As of May 2024, 134 countries are exploring CBDCs, including domestic and jointly cross-border CBDC programs, and approximately one third of these areas have embarked on pilot and implementation stages. (Source: Atlantic Council CBDC Tracker)

There is a growing interest on CBDCs' potential impact on the existing international monetary system, and the influence of CBDCs on currency invoicing power remains uncertain. The literature to date includes studies on the efficiency of CBDCs for retail payment systems (Iwańczuk-Kaliska, 2024), the facilitation of international transactions (Andolfatto, 2021), impacts on the banking sector (Schilling et al., 2024), and effects on financial system stability (Davoodalhosseini, 2022). Can CBDCs effectively enhance the attractiveness of a country's currency and thereby impact currency diversification? Initially proposed by China in 2014, CBDCs are still in developmental and pilot stages around the world, resulting in limited existing research due to data availability. This study endeavors to fill this gap by investigating the role played by CBDCs in enhancing a currency's invoicing capabilities, thereby providing a forward-looking prediction and reference for studies on national sovereign currency diversity. Given that CBDCs are primarily in the research and development stage, we concentrate on the development rather than the implementation of CBDCs. We argue that changes in invoicing practices, along with their impact on exchange rate stability and liquidity, will commence with CBDC development and be expected to become more pronounced as their progresses, which is currently only just beginning to occur. CBDCs are beginning to impact exchange rate stability and liquidity, which in turn reshapes the currency invoicing power. This process commences with the ongoing development of CBDC and be expected to become more significant as their implementation advances, a phase that is currently just beginning to occur.

The development of CBDCs not only facilitates settlement liquidity but also reduces currency fluctuation (Gopinath et al., 2020), which in turn enhances currency invoicing power by boosting market confidence in the corresponding currencies. Specifically, CBDCs are beneficial for maintaining the stability of the national exchange rate. CBDC based on peer-to-peer blockchain technology serve as an effective tool for monetary policy transmission and improve the effectiveness of central bank macroeconomic control (Bank for International Settlements, 2018, 2021b, 2022; Bank for International Settlements and the World Bank, 2022), thereby increasing exchange rate stability. Drawing on the theoretical framework proposed by Boz et al. (2017) regarding the choice of invoicing currencies, enhanced stability in a currency encourages manufacturers of homogeneous goods to select their domestic currency for invoicing the products. This choice minimizes price discrepancies with similar goods (Amiti et al., 2022). As the proportion of internationally traded goods priced in a country's currency increases, there is a corresponding convergence in the choice of invoicing currency among producers of homogeneous goods (Boz et al., 2022).

Consequently, CBDCs theoretically provide the possibility of increasing the liquidity of the national currency in the international market. CBDC cross-border payments can reduce the cost of cross-border transactions, significantly improve transaction transparency and payment efficiency. This makes the currency of a CBDC-developing country more attractive in international transactions. In June 2024, Saudi Arabia announced its decision not to renew the longstanding petrodollar agreement with the United States. Instead, it is exploring the use of mBridge, a CBDC cross-border payment platform led by the Bank for International Settlements (BIS), to price oil in currencies other than the U.S. dollar. This shift could potentially challenge U.S. dollar dominance, threatening its status as the world's primary reserve currency. With the development of CBDCs in various countries, cross-border CBDC payment platforms are also emerging. Manufacturers in countries developing CBDCs are more willing to select their national currency for invoicing their goods to enhance their bargaining power in price negotiations, reduce exchange rate risks, lower currency conversion costs, and avoid the policy uncertainty risks associated with invoicing in foreign currencies. As the liquidity of the national currency increases, international buyers are more willing to accept and hold that currency, which in turn promotes the country's invoicing ability.

Based on the theories of profit maximization, sticky prices, and trade elasticity (i.e., the sensitivity of trading volume to exchange rate changes), we hypothesize that the development of CBDCs promote the currency's invoicing capabilities by reducing exchange rate fluctuation and increasing foreign exchange liquidity. Following the framework of Amiti et al. (2022) and Gopinath et al. (2020), we construct a model of currency invoicing power. Utilizing a sample of the top 50 countries by constant GDP in 2022, covering the period from 2005 to 2022, we conduct a cross-country analysis to assess whether the development of a country's CBDC promotes the currency invoicing power. The findings indicate that the development of a country’s CBDC significantly enhances its currency's power in trade invoicing. These results remain significant after a series of robustness tests. Mechanism analyses suggest that the development of a country’s CBDC enhances its currency invoicing power by reducing exchange rate volatility. We further find that this enhancement is stronger in CBDC’s pilot countries.

The primary contributions of this essay can be summarized in three key points. First, this study enriches the research on CBDC applications. Previous studies have mostly explored CBDCs from theoretical and conceptual perspectives due to limited data availability. Das et al. (2023) suggest that CBDC has the potential to change financial stability and the way monetary policy is implemented. Bindseil (2020) compares the financial account implications of CBDC with those of crypto assets, stablecoins, and narrow bank digital money. Our research differentiates itself by empirically providing new insights into the growing interest in CBDCs' potential impacts on the existing international monetary system and how CBDC’s development affects the currency invoicing power in international trade.

Second, our study provides the first piece of empirical evidence on the mechanisms through which CBDCs impact currency invoicing capability in international trade. Our findings indicate that the development of a country's CBDC significantly enhances its currency's trade invoicing power by mitigating exchange rate volatility and increasing in currency liquidity in international foreign exchange market, and then making their own currency more attractive for invoicing purposes. This contribution not only underscores the practical implications of CBDCs but also fills a gap in the literature by detailing the pathways by which CBDCs influence currency invoicing capability.

Third, this study offers a new perspective on understanding global currency diversity, providing valuable insights for policymakers. Our findings suggest that the development of CBDCs by various countries significantly enhance the national currency invoicing power, implying that promoting and accelerating the development of CBDCs can increase the use of national currencies in international trade. This development of CBDCs is not merely a technological advancement but also a strategic tool for increasing national currency internationalization and may improve national currency internationalization.

Concurrently, this research enriches the currency pricing theory with a global perspective by using a broader and more comprehensive sample to explain how CBDCs impact currency selection. By considering the diverse economic environments and policy landscapes of different countries, this global analysis is critical for developing a more universally applicable currency invoicing theory.

This study assesses the impact of CBDCs development on currency invoicing capability in international trade invoicing. The remainder of this chapter is structured as follows. Section 2 reviews the existing literature and develops the hypotheses. Section 3 describes the methodology and data construction. Section 4 reports primary findings, and further addresses endogeneity concerns. Section 5 discusses the findings and presents conclusions.

2. Literature review and hypothesis development

2.1 Currency dominance and the rise of CBDCs

The currency dominance in trade invoicing plays a crucial role in global financial stability (Goldberg & Tille, 2008). The U.S. dollar remains dominant despite the Russia-Ukraine military conflict in 2022 and the COVID-19 pandemic in 2020 (Gerding & Hartley, 2024). As the primary vehicle currency, the dominant status leads to an excessive reliance on the U.S. dollar in global financial markets. It would trigger instability in global financial markets if the United States changes its monetary policy (Jaramillo & Weber, 2013) or impose sanctions on other countries leveraging its dominant status (Buckley & Trzecinski, 2023). Dollar appreciation increases imported inflation (McCarthy, 2007) , while rising U.S. dollar interest rate can cause foreign exchange reserves losses, deterioration of payments balance, currencies depreciation, and even economic recession in other countries, as seen in the 1997 Asian financial crisis.

In recent years, Growing geopolitical conflicts have prompted efforts to actively explore strategies for de-dollarization, including Russia's "Ruble Settlement Order" introduced in 2022, ASEAN "Local Currency Transaction" initiative signed in 2023, and China's extensive networks of bilateral currency swap agreements (People's Bank of China, 2023) and the Belt and Road Initiative (Aoyama, 2016). Besides, BRICS+[1] has undertaken collective measures to advance de-dollarization efforts (Liu & Papa, 2022).Emerging non-dollar infrastructures, e.g. CIPS, INSTEX, and the ASEAN[2] contactless QR code payment system, enable cross-border transactions in local

[1] BRICS countries are Brazil, Russia, India, China, and South Africa, while BRICS+ refers to the BRICS group plus additional economies such as Saudi Arabia, United Arab Emirates, Egypt, Iran, and Argentina.
[2] The ASEAN countries include the Philippines, Indonesia, Malaysia, Singapore, and Thailand.

currencies and reduce dollar reliance.

In this context, CBDCs are expected as a potential means to reduce reliance on the U.S. dollar and promote the use of local currencies in international settlements (Buckley & Trzecinski, 2023). Since 2014, research on CBDCs worldwide has been rapidly increasing. The central banks of Iran and Russia are issuing CBDCs to circumvent sanctions imposed by the United States and other countries. Besides the rapid development of domestic CBDCs research, there is a growing interest on cross-border payments among various CBDCs. The current international monetary system remains heavily reliant on SWIFT with high costs for international transactions (Ghasseminejad & Jahan-Parvar, 2021). CBDCs have the potential to address these inefficiencies by reducing dependency on intermediaries, lowering transaction fees, minimizing currency conversion costs, and improving payment and settlement efficiency. Countries are developing various multilateral CBDC platforms to facilitate interoperability and connectivity among CBDC frameworks globally. Such as mBridge[1], Dunbar[2], Jasper-Ubin[3], Digital Euro. The CBDC network also has the potential to push the international financial system toward becoming more decentralized (Wang & Gao, 2024).

2.2 Invoicing currency in international trade

Boz et al. (2017) develop a method to measure the usage of invoicing currencies and found that the U.S. dollar acts as the primary invoicing currency in global trade. When choosing the currency for invoicing, export-oriented economies prefer to use the producer currency, because it reduces the impact of exchange rate fluctuations on

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[1] The central banks of China, Hong Kong, Thailand, and the United Arab Emirates (UAE) have collaborated in the project called mBridge sponsored by the Bank for International Settlements (BIS).
[2] Led by the BIS Innovation Hub in partnership with the central banks of Australia, Malaysia, Singapore, and South Africa, this project aims to develop prototypes for shared platforms that enable international settlements with multiple CBDCs.
[3] A collaboration between the Bank of Canada and the Monetary Authority of Singapore aims to investigate the potential interoperability of Distributed Ledger Technology in facilitating cross-border payments.

exporters and avoid the frequent use of financial instruments to hedge foreign exchange risk (Bartram & Bodnar, 2007). Invoicing in their domestic currency can enhance the effectiveness of their domestic monetary policy, making the transmission effects of monetary policy more apparent, thereby ensuring more stable cash flows for exporters (Goldberg & Tille, 2008). However, not all economies have the option to use their domestic currency for invoicing. For countries with smaller currency markets and weak macroeconomic fundamentals, it becomes difficult for them to rely on their domestic currency for accounting and trading purposes (International Monetary Fund, 2023).

The development and implementation of CBDCs can boost a country's currency influence, potentially encouraging exporters to price goods in the national currency. CBDCs facilitate seamless global use, particularly in cross-border payments, increasing currency liquidity and reducing exchange costs (Bank for International Settlements, 2020). Especially, for major economies such as the EU, China, Japan, the UK, and India with high international trading volumes, CBDCs are expected to break single-currency settlement systems, promoting currency diversification, and enhancing cross-border settlement efficiency. Current primary cross-border payment platforms, such as the SWIFT, are incentivized to operate as closed-loop systems, leading to high barriers and high costs (Bank for International Settlements, 2020). This setup can potentially lead to a concentration and monopolies. Even with multiple systems available, the use of different messaging standards can create fragmentation payment systems (Buckley & Trzecinski, 2023). This fragmentation increases costs and complexities when transacting across platforms. For major economies e.g. the EU, China, Japan, the UK, and India with high international trading volumes, CBDCs are expected to break single-currency settlement systems and diversify currency diversification. CBDCs offer a unified solution to transfer efficiently and securely by improving interoperability[1] across disparate closed payment systems (Bank for International Settlements, 2020).

2.3 Factors affecting the currency in international trade invoicing

The stability of the currency value and monetary liquidity are important factors that affect firms' currency invoicing power. Gopinath and Stein (2021) propose that International Trade Invoicing, Bank Funding, Corporate Borrowing, Central Bank Foreign Exchange Reserves, and Risk-Free Rate Expected Returns are five factors that influence currency dominance. Amiti et al. (2014, 2022) argue that firms choose a currency as the invoicing currency for stable revenue and market share, opting for currencies that are relatively stable in value. Coppola et al. (2023) suggest that monetary liquidity plays a critical role in determining the currency firms choose for debt denomination. To consider the managerial incentives for currency mismatching by corporations, Smith and Stulz (1985) argue that tax convexity, such as progressive tax systems, is a key driver for corporate hedging. The introduction of CBDC could alter this dynamic, reducing hedging needs by improving tax transparency and efficiency, simplifying cash flow management, and integrating with national tax systems to lower compliance costs.

2.4 Hypothesis development

Based on the exchange rate pass-through into consumer prices, as more firms use a country's currency for invoicing, the product prices closely track the fluctuations of bilateral exchange rate (Amiti et al., 2022).

Specifically, the trade elasticity theory indicates that trading volumes are sensitive

[1] Interoperability refers to the seamless interaction and transaction among various CBDC systems, achieved through standardized protocols, APIs, distributed ledger technology, cross-chain interoperability solutions, and gateway systems, enabling efficient and secure cross-border payments.

to exchange rate changes, with significant variations in trade elasticity across different countries (Krugman, 1980). According to the purchasing power parity theory, exchange rate changes should reflect the relative price levels between countries (Cassel, 1918). When firms choose country *i*'s currency as the invoicing currency, their prices are influenced by fluctuations in country *i*'s exchange rate. As more firms in the two trading countries use a country's currency (country *i*) as the invoicing currency , their product prices become more susceptible to the fluctuations in country *i*'s exchange rate (Amiti et al., 2022; Boz et al., 2017).

The prices stickiness leads to a significant ERPT. Typically, manufacturers would keep their product prices unchanged in the short term, demonstrating price stickiness (Amiti et al., 2022). When transactions are invoiced in exporting currency *i*, producers typically do not immediately adjust the prices even if exchange rate changes, and instead maintaining the original price in the short run. Since producers do not frequently change prices in response to exchange rate fluctuations, any changes in bilateral exchange rate will cause the price changes of goods, when converted to the destination currency *j*, to reflect those fluctuations.

The currency substitution effect further illustrates how exchange rate changes are transmitted to commodity prices (Girton & Roper, 1981). Firms tend to select the same currency for invoicing as other firms in the market to minimize price discrepancies with homogeneous products (Calvo & Gramont, 1992). The more the international market trusts producer currency *i*, the more businesses and consumers are willing to use producer currency *i* for invoicing. As a higher proportion of internationally traded goods priced in producer currency, there is greater convergence among producers in their choice of invoicing currency of homogeneous goods. Consequently, the ERPT on commodity prices between producer country *i* and destination country *j* becomes more pronounced, with changes in the exchange rate significantly reflected in import prices (Goldberg & Knetter, 1996).

Based on the above, if a currency exhibits a high exchange rate pass-through, it has greater influence in the international market, as more countries choose for it as an invoicing currency, especially when producer currency *i* is widely used in international bilateral transactions. The introduction of CBDC can increase market trust, leading to more international trade being invoiced in country *i*'s currency. Therefore, we expect that the development of CBDC affects firms' currency invoicing power by enhancing the exchange rate pass-through, and we propose the following hypothesis 1.

Hypothesis 1: *The development of CBDC enhances currency invoicing capability of the country's currency.*

However, ERPT is not constant. Its extent is significantly influenced by economic uncertainty, market conditions, and policy environments (Cheikh et al., 2023). The signal of CBDC development helps promote exchange rate stability. The issuance and use of CBDCs with higher transparency will improve monetary policy transmission mechanisms (Bank for International Settlements, 2018, 2021a, 2022), offer real-time data and better monitoring capabilities (Bank for International Settlements, 2020), allowing central banks to respond more quickly and accurately when taking measures to stabilize exchange rates.

Additionally, a relatively stable exchange rate is an important factor for profit-maximizing firms when choosing a currency for invoicing. Exchange rate volatilities increase the risk of fluctuating payment values for exporters (country *i*), leading to potential financial losses and higher costs due to the need for hedging. Opting for a currency with low volatility minimizes this risk and ensures stable income. Further, exchange rate stability reflects broader economic stability, boosting international confidence in the currency and potentially improving its global status and influence (McKinnon, 1988).

Therefore, we suppose CBDCs will enhance the invoicing power of currencies by decreasing exchange rate volatility, and we propose the following hypothesis 2.

Hypothesis 2: *CBDC development signals enhance currency invoicing capabilities by reducing exchange rate volatility and increasing exchange rate stability.*

Developing CBDC helps facilitate easier access to financial services, which increases demand for the national currency when combined with integration into open finance systems. The higher demand boosts liquidity in the currency market, which in turn makes the currency more attractive for international transactions (Avgouleas & Blair, 2024). As a result, manufacturers are more inclined to use their own currency for bargaining power, reducing exchange rate risks and minimizing the uncertainties from foreign currency invoicing. Based on these factors, we propose the following hypothesis 3.

Hypothesis 3: *CBDC development signals enhance currency invoicing capabilities by promoting foreign exchange turnover and increasing exchange rate liquidity.*

3. Methodology and data

Existing studies on the choice of invoicing currency in trade include findings by Engel (1993), who note that besides the pricing of a single homogeneous product, there are significant differences in the relative prices of products across different countries, indicating that the Law of One Price does not hold. To explain deviations from the Law of One Price, Betts and Devereux (2000), building on the new open macroeconomic framework created by Obstfeld and Rogoff (2000), introduced the theory of pricing to market and currency invoicing to explain the non-correlation between trade prices and exchange rates. They argue that exporting firms segment markets and choose invoicing currencies on an economy-wide basis. Devereux et al. (2004) endogenize the choice of currency for pricing commodities, suggesting that firms in country *i* select the invoicing currency based on the monetary policy stability of the economies involved in the transaction. Boz et al. (2017) develop a method to measure the usage of invoicing currencies and find that the U.S. dollar acts as the primary invoicing currency in global trade, with a significant number of goods priced in dollars in what has been called the dominant currency paradigm (Gopinath et al., 2020).

3.1 Econometric model

By following Gopinath et al. (2020) and Amiti et al. (2022) methods of measuring currency choice of invoicing, we construct the following equation to examine the influence of CBDC progress on currency invoicing power. Considering that CBDC research projects do not begin at the same time across countries, we construct a staggered Difference-in-differences setting by including the interaction term of exchange rate and CBDC progress as for moderating effect.

$$\Delta P_{ij,t} = \beta_1 \Delta E_{ij,t} + \beta_2 Shock_{i,t} * \Delta E_{ij,t} + \beta_3 Shock_{i,t} + \gamma X_{ij,t} + \alpha_{ij} + \varepsilon_{ij,t} \quad (1)$$

Where $\Delta P_{ij,t}$ denotes the change in the log of price, the total value divided by the total quantity, of goods exported from country i to country j in year t. The pricing of goods is invoiced in country i's currency while measured in terms of country j's currency, with an increase indicating an appreciation of the currency i.

The primary explanatory variable $\Delta E_{ij,t}$ denotes the changes of the log of bilateral exchange rate between country i and country j in year t. A larger β_1 coefficient indicates a stronger trade pricing capability of country i's currency.

The interaction term of $Shock_{i,t} * \Delta E_{ij,t}$ is our main variable of interest. We include CBDC shock as a moderating effect.

We employ the staggered CBDC development status as an exogenous shock represented by $Shock_{i,t}$, *which is a* dummy variable presenting if country i has announced a CBDC research program in year t. Further details of CBDC announcements are presented in Appendix B. $X_{ij,t}$ refers to a set of control variables, including $\Delta Volume_{ij,t}$, $\Delta GDP_{i,t}$, $\Delta GDP_{j,t}$, $Inflation_{i,t}$, $Inflation_{j,t}$, ΔWTI_t, $LnVIX_t$, $Bitcoin_{i,t}$ and country level paired fixed effects are represented by α_{ij}[1].

3.2 Sample and data

According to the StatisticTimes database, the total GDP of the top 50 countries account for about 91% of global economy. Considering our focus on international bilateral trade and the typically lower trade volumes of smaller economies, our initial sample includes the top 50 countries ranked by constant GDP in 2022. For further analysis, we focus on 7 countries worldwide that had initiated CBDC pilots by 2022, regardless of their GDP ranking. Since the first country began researching CBDCs in 2014, we collect data from nine years before 2014 to nine years after 2014 as our sample

[1] Since the year effects have already been accounted for in the control variables, the fixed effects model here do not include year as a control factor.

interval. Our final sample covers the period from 2005 to 2022.

The goods exported bilateral trade data are sourced from the BACI dataset of the CEPII. The data used to construct CBDC shock is retrieved from Atlantic council (2024). The data of Exchange rate, Inflation, GDP, Trading volume come from the World Bank's WDI database. WTI and VIX data are obtained from the St. Louis Fed’s FRED database. The indicator of exchange rate volatility used in the mechanism test, measuring in the variance of real effective exchange rate, is sourced from the FRED database. The foreign exchange turnover data also used in the mechanism test is sourced from BIS Triennial Central Bank Survey (2022). To avoid the influence of outlier observations, all continuous variables are winsorized at the 1% and 99% levels. Variable definitions are presented in Appendix A.

The situation within the European Union is relatively complex. In the EU27, there are seven countries—Bulgaria, Czechia, Denmark, Hungary, Poland, Romania, and Sweden—that are part of the European Union but haven't adopted the Euro as their official currency yet. So, for these countries, we use the exchange rate data of their own national currencies. Meanwhile, for the Eurozone member countries (EU20), such as Germany, France, Italy, and others, we use the Euro exchange rate and the digital Euro data as the relevant indicators.

4. Empirical analysis

4.1 Descriptive statistics

Table 3.1 presents the descriptive statistics for the key variables. The mean value of $Shock_{i,t}$ is 0.223, suggesting that approximately 22.3% of our sample countries or regions have initiated research on CBDCs by 2022. This relatively high percentage highlights the importance and the trend of CBDC research and development in the context of global monetary reform. The mean value of $\Delta GDP_{j,t}$ is 3.266%, slightly higher than the $\Delta GDP_{i,t}$ at 3.026%, and the mean value of $Inflation_{j,t}$ (6.244%) is higher than that of $Inflation_{i,t}$ at 4.957%. This is primarily because country *i*, selected from the top 50 countries by GDP in 2022, has both lower GDP growth rate and inflation rate within the sample period.

Table 3.1 Descriptive statistics

Variable	Observation	Mean	Standard deviation	Minimum	Maximum
$\Delta P_{ij,t}$	146,421	0.061	0.865	-10.120	10.950
$\Delta E_{ij,t}$	146,421	0.006	0.149	-0.941	4.811
$Shock_{i,t}$	146,421	0.223	0.416	0	1
$Bitcoin_{i,t}$	146,421	0.833	0.373	0	1
$\Delta Volume_{ij,t}$	146,421	0.031	1.297	-16.350	16.320
$\Delta GDP_{i,t}$	146,421	3.026	3.614	-11.170	24.480
$\Delta GDP_{j,t}$	146,421	3.266	5.718	-54.340	86.830
$Inflation_{i,t}$	146,421	4.957	7.624	-16.580	96.040
$Inflation_{j,t}$	146,421	6.244	10.950	-30.200	235.500
ΔWTI_t	146,421	-0.256	39.740	-137.100	44.000
$LnVIX_t$	146,421	2.888	0.308	2.406	3.487
$Variance_{i,t}$	134,495	12.380	33.670	0.071	609.600
$Turnover_{i,t}$	125,725	2.357	1.502	0	7.043

This table provides the descriptive statistics for the variables used in the study. The sample countries are ranked among the top 50 based on constant GDP for the year 2022. The period spans from 2005 to 2022. Comprehensive definitions of the variables are detailed in Appendix A.

4.2 Correlation matrix

Table 3.2 provides the correlation matrix for the main variables used in our analysis. The correlation coefficients between independent variables are small, suggesting that multicollinearity is not a serious issue in this study. The correlation coefficient between $\Delta E_{ij,t}$ and $\Delta P_{ij,t}$ is 0.082 , which is statistically significant at the 1% level. This preliminarily result suggests a positive transmission effect of exchange rates on prices. The development of CBDCs and Bitcoin is significantly positively correlated at the 1% level, which supports the interesting fact that the rise of Bitcoin has accelerated technological advancements in blockchain and distributed ledger technologies (DLT). These technologies become the infrastructure required for CBDCs and facilitate the development of CBDCs. The correlation coefficients between CBDC shock and the GDP growth rates of country *i* and *j* are both negative, which is consistent with the views of Carapella and Flemming (2020). They point out that in the early stages of CBDC development, adjustments in monetary policy might take some time to be effectively transmitted through the new mechanism, thereby negatively impacting economic growth in the short term.

Table 3.2 Correlation matrix

	$\Delta P_{ij,t}$	$\Delta E_{ij,t}$	$Shock_{i,t}$	$Bitcoin_{i,t}$	$\Delta Volume_{ij,t}$	$\Delta GDP_{i,t}$	$\Delta GDP_{j,t}$	$Inflation_{i,t}$	$Inflation_{j,t}$	ΔWTI_t	$LnVIX_t$
$\Delta P_{ij,t}$	1										
$\Delta E_{ij,t}$	0.082***	1									
$Shock_{i,t}$	0.023***	0.008***	1								
$Bitcoin_{i,t}$	-0.009***	-0.043***	0.240***	1							
$\Delta Volume_{ij,t}$	-0.696***	-0.007**	-0.028***	-0.021***	1						
$\Delta GDP_{i,t}$	0.033***	0.062***	-0.057***	-0.242***	0.034***	1					
$\Delta GDP_{j,t}$	0.011***	-0.027***	-0.094***	-0.230***	0.061***	0.307***	1				
$Inflation_{i,t}$	0.026***	-0.330***	0.004	-0.058***	0.007**	0.176***	0.076***	1			
$Inflation_{j,t}$	0.061***	0.319***	0.011***	-0.116***	0.005**	0.122***	0.106***	0.071***	1		
ΔWTI_t	0.012***	0.046***	0.136***	-0.099***	0.001	-0.089***	-0.040***	0.072***	0.069***	1	
$LnVIX_t$	0.005*	0.028***	0.030***	0.400***	-0.006**	-0.040***	-0.032***	0.033***	0.030***	0.278***	1

This table presents the correlation matrix among the variables of interest for the sample of the top 50 GDP countries. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. All variables are defined in Appendix A.

4.3 Baseline results

We follow Boz et al. (2017) methods of measuring the invoicing power of currency by examining the relationship between the changes of commodity price and the changes of exchange rates. $\Delta E_{ij,t}$ represents the exchange rate changes between country *i* and *j*, while $\Delta P_{ij,t}$ represents the price changes of goods exported from country *i* to country *j*. β_1 is the coefficient of $\Delta E_{ij,t}$. The larger the β_1, the greater the impact of exchange rate changes between countries *i* and *j* on price changes. Because as more manufacturers price goods in their own currency *i*, the exchange rate changes between country *i* and *j* will more directly affect the goods prices, making the pass-through effect of exchange rate changes more obvious, reflected in an increase in the value of β_1. We include CBDC shock as a moderating effect. The coefficient of $Shock_{i,t} * \Delta E_{ij,t}$ (β_2) captures the effect of CBDCs' development on the currency *i*'s invoicing power. Specifically, a positive coefficient of $\Delta E_{ij,t} * Shock_{i,t}$ indicates that the development of CBDC strengthens the exchange rate pass-through from $\Delta E_{ij,t}$ to $\Delta P_{ij,t}$, while a negative coefficient suggests that CBDC inhibits this effect.

The baseline regression results are shown in Table 3.3 based on Equation (1). Column (1) includes the country level paired fixed effects of country *i* and country *j* to control unobserved differences between countries. Column (2) includes control variables for the global macroeconomic characteristics of country *i* and country *j*.It can be observed that the coefficients of $\Delta E_{ij,t}$ in Columes (1) and (2) are positive, reflecting that the higher $\Delta E_{ij,t}$, the greater the price variation of goods priced in country *i*'s currency. This result aligns with the literature on exchange rate pass-through, which highlights the significant transaction effect of exchange rate fluctuations on goods prices (Amiti et al., 2022; Gopinath et al., 2020). The coefficient of interaction term $\Delta E_{ij,t} * Shock_{i,t}$ in Column (2) is our main focus of interest and is statistically positive significant at the 1% level. In terms of economic significance. This result indicates that the development of CBDCs magnifies the exchange rate pass-through effect from $\Delta E_{ij,t}$ to $\Delta P_{ij,t}$, thereby promoting more exporters (country i) to choose their own currency as the invoicing currency after developing CBDC projects, supporting Hypothesis 1. This is likely because more exporters (in country i) are willing to use domestic currency for invoicing after developing CBDC projects. $\Delta Volume_{ij,t}$ is significantly negatively correlated with $\Delta P_{ij,t}$, indicating that the more products country i imports from country j, the less the product prices increase. Both $Inflation_{i,t}$ and $Inflation_{j,t}$ are significantly positively correlated with $\Delta P_{ij,t}$, this may be because inflation lead to higher production costs and reduce consumers' purchasing power, which are passed on to product prices, thereby raising export prices and affecting import prices.

Table 3.3 The influence of CBDCs' development on currency pricing power in international bilateral trade

	$\Delta P_{ij,t}$	$\Delta P_{ij,t}$
	(1)	(2)
$\Delta E_{ij,t}$	0.604***	0.594***
	(22.827)	(30.344)
$\Delta E_{ij,t} * Shock_{i,t}$	0.134***	0.218***
	(3.321)	(7.585)
$Shock_{i,t}$	0.055***	0.009**
	(9.730)	(2.130)
$Bitcoin_{i,t}$		0.008
		(1.415)
$\Delta Volume_{ij,t}$		-0.473***
		(-366.720)
$\Delta GDP_{i,t}$		0.007***
		(12.290)
$\Delta GDP_{j,t}$		0.008***
		(19.004)
$Inflation_{i,t}$		0.008***
		(21.010)
$Inflation_{j,t}$		0.002***
		(8.828)
ΔWTI_{t}		0.000***
		(4.217)
$LnVIX_{t}$		-0.015**
		(-2.443)
Paired FE	Yes	Yes
Observations	146,315	146,315
Adj. R-squared	0.024	0.509

This table reports the baseline results. Appendix A presents the detailed variable definitions. All continuous variables are winsorized at the 1% level in each tail. The country level paired fixed effects and *t*-statistics are presented in parentheses, where *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

4.4 Mechanism analysis

4.4.1 Exchange rate volatility

We consider that a stable exchange rate is one of the mechanisms by which CBDC enhances currency invoicing capability. According to Hypothesis 2 development, higher exchange rate volatility is expected to reduce a firm's motivation to choose that currency for invoicing. Additionally, the introduction of CBDC development for a country may contribute to reducing the volatility of its exchange rate. To this end, we examine whether the introduction of CBDC can promote a country's currency invoicing power by reducing the exchange rate volatilities, using a two-step approach.

Specifically, in the first step we establish the relationship between CBDC shock and exchange rate volatilities. We use monthly exchange rate data (sourced from the FRED database) to calculate the annual variance of real broad effective exchange rate of country *i*, estimating exchange rate volatility. In the second step, we introduce a triple interaction term $\sigma^2_{Ei,t} * Shock_{i,t} * \Delta E_{ij,t}$ to examine the moderating effect of exchange rate volatility on the interaction term of $\Delta E_{ij,t} * Shock_{i,t}$.

As shown in Table 3.4, Column (1) indicates a significant decrease in the volatility of the exchange rates of currencies after developing CBDCs. It supports the view that CBDCs can reduce the impact of exchange rate volatility. In Column (2), the coefficient of $\sigma^2_{Ei,t} * Shock_{i,t} * \Delta E_{ij,t}$ is significantly negative, indicating that exchange rate volatilities inhibit the exchange rate pass-through effect. This supports Hypothesis 2 that the development signals of CBDC can enhance the currency pricing capability by reducing exchange rate volatility.

4.4.2 Foreign exchange liquidity

Additionally, we suppose the increased liquidity of foreign exchange as another mechanism by which CBDCs enhance currency invoicing capability. Increased liquidity of national currency in international market encourages manufacturers to choose their own currency for invoicing. Because it strengthens their bargaining power in price negotiations, mitigates exchange rate risks, and avoids uncertainties linked with foreign currency invoicing. The development of CBDC can further enhance this liquidity by lowering cross-border payment costs, significantly enhancing transparency, and improving settlement efficiency. We choose the OTC foreign exchange turnover by countries from the BIS database as the liquidity indicator.

Similar with the mechanism test of exchange rate volatility, we first establish the relationship between CBDC shock and currency liquidity. Then we further introduce a triple interaction term ($turnover_{i,t}$ * $Shock_{i,t}$ * $\Delta E_{ij,t}$) to examine the moderating effect of foreign exchange liquidity on the interaction term of $\Delta E_{ij,t}$ * $Shock_{i,t}$. The results are presented in Table 3.4 Column (3) and Column (4). Column (3) indicates that the development signals of CBDC significantly enhance currency liquidity at the 1% significant level. Besides, Column (4) reveals the coefficient of $turnover_{i,t}$ * $Shock_{i,t}$ * $\Delta E_{ij,t}$ is positive at the 1% significant level. These results suggest that the enhanced currency liquidity promote the exchange rate pass-through effect of exchange rate changes to goods prices changes. This supports Hypothesis 3 that CBDC can enhance the currency invoicing power by boosting currency liquidity.

Table 3.4 Mechanism analysis

	Volatility		*Liquidity*	
	$\sigma^2_{Ei,t}$	$\Delta P_{ij,t}$	$turnover_{i,t}$	$\Delta P_{ij,t}$
	(1)	(2)	(3)	(4)
$\Delta E_{ij,t}$		0.620***		0.638***
		(29.817)		(30.653)
$\sigma^2_{Ei,t} * E_{ij} * Shock_{i,t}$		-0.002***		0.047***
		(-3.094)		(2.804)
$E_{ij} * Shock_{i,t}$		0.267***		0.077
		(8.716)		(1.426)
$Shock_{i,t}$	-4.544***	0.008*	0.025***	0.004
	(-33.345)	(1.832)	(9.618)	(0.862)
$Bitcoin_{i,t}$	2.605***	0.011*	0.094***	0.009*
	(14.904)	(1.884)	(28.339)	(1.656)
$\Delta Volume_{ij,t}$	-0.076*	-0.478***	-0.003***	-0.497***
	(-1.822)	(-353.634)	(-3.257)	(-351.195)
$\Delta GDP_{i,t}$	-0.908***	0.007***	-0.016***	0.006***
	(-49.483)	(10.993)	(-46.361)	(10.489)
$\Delta GDP_{j,t}$	0.025*	0.008***	0.003***	0.008***
	(1.802)	(18.166)	(13.253)	(19.043)
$Inflation_{i,t}$	0.209***	0.011***	0.001***	0.010***
	(15.802)	(24.203)	(2.964)	(20.764)
$Inflation_{j,t}$	0.144***	0.002***	0.002***	0.002***
	(17.227)	(7.124)	(11.938)	(7.244)
ΔWTI_t	-0.024***	0.000***	-0.000***	0.000***
	(-16.648)	(4.793)	(-4.302)	(3.760)
$LnVIX_t$	-0.673***	-0.018***	0.131***	-0.022***
	(-3.429)	(-2.884)	(34.931)	(-3.588)
Paired FE	Yes	Yes	Yes	Yes
Observations	134,401	134,401	125, 649	125, 649
Adj. R-squared	0.396	0.512	0.952	0.525

This table presents the impact of CBDC shock on international settlement through mitigating exchange rate volatilities ($\sigma^2_{Ei,t}$) and increasing foreign exchange liquidity ($turnover_{i,t}$). The samples in Column (1) and (2) include the top 50 countries except three countries of Bangladesh, Egypt, and Vietnam due to data limitation, while Column (3) and (4) cover the sample of all the top 50 countries. Column (1) reports the impact of CBDC shock on exchange rate volatilities of country *i*. Column (2) presents the moderating effect of $\sigma^2_{Ei,t}$ on $\Delta E_{ij,t} * Shock_{i,t}$. Column (3) reveals the impact of CBDC shock on foreign exchange turnover of country *i*. Column (4) presents the moderating effect of $turnover_{i,t}$ on $\Delta E_{ij,t} * Shock_{i,t}$. Controls are the same as in Table 3.3. All continuous variables are winsorized at the 1% level in each tail. Appendix A presents the detailed variable definitions. *t*-statistics are presented in parentheses, where *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

4.5 Robustness check

The global financial crisis could impact our findings by introducing significant economic volatilities, such as sharp declines in GDP, increased unemployment rates, volatile exchange rates, and disruptions in financial markets. These fluctuations may create an unstable economic environment, affecting manufacturers' operations and subsequently interfering with their currency invoicing power. To check the robustness of the baseline regression, we consider the impact of the global financial crisis on our sample by excluding data of the years 2008 and 2009, as shown in Panel A in Table 3.5. In the meantime, panel B expand the sample to 186 countries during the same year period of baseline regression. The findings indicate that both $\Delta E_{ij,t}$ and $\Delta P_{ij,t}$ are positively related at the 1% significance level. Furthermore, the coefficient of the interaction term $\Delta E_{ij,t} * Shock_{i,t}$ is significantly positive at the 1% level. These results are consistent with the baseline regression, confirming the robustness of the initial findings.

Table 3.5 Robustness check

Panel A. Consider the impact of global financial crisis (Sample: Top 50 countries; Year Period: 2005-2022 excluding 2008 and 2009)		
	$\Delta P_{ij,t}$	$\Delta P_{ij,t}$
	(1)	(2)
$\Delta E_{ij,t}$	0.594***	0.604***
	(20.640)	(28.523)
$\Delta E_{ij,t} * Shock_{i,t}$	0.145***	0.213***
	(3.521)	(7.304)
$Shock_{i,t}$	0.056***	0.013***
	(9.628)	(2.855)
$Bitcoin_{i,t}$		-0.020***
		(-3.377)
$\Delta Volume_{ij,t}$		-0.476***
		(-346.010)
$\Delta GDP_{i,t}$		0.004***
		(6.511)
$\Delta GDP_{j,t}$		0.008***
		(16.773)
$Inflation_{i,t}$		0.007***
		(17.613)
$Inflation_{j,t}$		0.002***
		(5.133)
ΔWTI_t		0.000
		(0.766)
$LnVIX_t$		0.035***
		(4.654)
Paired FE	Yes	Yes
Observations	129,883	129,883
Adj. R-squared	0.033	0.516

Panel B. Expand the sample from 50 countries to186 countries (Sample: 186 countries; Year Period: 2005-2022)		
	$\Delta P_{ij,t}$	$\Delta P_{ij,t}$
	(1)	(2)
$\Delta E_{ij,t}$	0.569***	0.572***
	(24.626)	(32.401)
$\Delta E_{ij,t} * Shock_{i,t}$	0.156***	0.203***
	(2.762)	(4.926)
$Shock_{i,t}$	0.055***	0.019***
	(6.555)	(2.992)
$Bitcoin_{i,t}$		-0.005
		(-1.030)
$\Delta Volume_{ij,t}$		-0.421***

		(-544.610)
$\Delta GDP_{i,t}$		0.004***
		(9.348)
$\Delta GDP_{j,t}$		0.007***
		(16.179)
$Inflation_{i,t}$		0.005***
		(18.750)
$Inflation_{j,t}$		0.003***
		(9.241)
ΔWTI_t		0.000**
		(2.334)
$LnVIX_t$		-0.001
		(-0.094)
Paired FE	Yes	Yes
Observations	363,815	363,815
Adj. R-squared	0.034	0.489

This table reports the robustness checks. Panel A shows the sample including the top 50 countries. In Panel A, considering the impact of the 2008 financial crisis, we exclude data of the years 2008 and 2009. Meanwhile, Panel B expands the sample to 186 countries in the world during the same year period of baseline regression. Appendix A presents the detailed variable definitions. All continuous variables are winsorized at the 1% level in each tail. The country level paired fixed effects and *t*-statistics are presented in parentheses, where *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

4.6 PSM test

Factors such as the activity of goods in bilateral trading markets, the stability of currency values relative to the prices of goods, and the economic growth may influence a country's capacity to develop a CBDC. To mitigate selection bias, we follow Chen et al. (2017) and use propensity score matching (PSM) to construct treatment and control groups. We employ a logit model where the dependent variable is a dummy setting value of one if the country announces a CBDC in a given year, and zero otherwise. We use the propensity scores to match countries in the two groups and produce the treatment-control pairs[1]. In terms of the independent variables, we perform a one-to-one PSM procedure based on country characteristics including covariates of trading volume ($Volume_{ij,t}$) in international bilateral trade between country i and country j, the inflations of country i and country j ($Inflation_{i,t}$ and $Inflation_{j,t}$), and country i and country j's GDP growth ($\Delta GDP_{i,t}$ and $\Delta GDP_{j,t}$). This approach yields a treatment group and a matching control group with countries having very similar characteristics.

Table 3.6 reports the PSM results. As shown in Panel A, Column (1) and Column (2) report the probit regression tests before and after matching, separately. In Columns (2), 80% of the covariates overall exhibit no significant differences after matching. The probit model produces a pseudo R-squared of 0.0124 and a p-value from the *chi*-square test below 0.001, suggesting that the model specification captures a significant amount of variation in the choice variable. Panel B presents the staggered difference-in-differences regression using the matched sample. The Column (2) in Panel B includes country level paired fixed effects. The results consistently show statistically significant and positive coefficients for the interaction term of $\Delta E_{ij,t} * Shock_{i,t}$ and $\Delta P_{ij,t}$, indicating that our findings are robust after concerning sample selection bias.

[1] We match using the nearest neighbor within a 0.01 caliper (distance) to improve matching accuracy.

Table 3.6 PSM test

Panel A. Probit regressions with pre-matched and post-matched samples		
	Pre-match	Post-match
	(1)	(2)
$\Delta Volume_{ij,t}$	0.001***	0.001
	(6.82)	(1.37)
$\Delta GDP_{i,t}$	-0.018***	-0.002
	(-16.55)	(-1.30)
$\Delta GDP_{j,t}$	-0.028***	-0.009***
	(-32.97)	(-8.24)
$Inflation_{i,t}$	0.003***	0.001
	(5.74)	(0.43)
$Inflation_{j,t}$	0.004***	0.001
	(8.12)	(0.97)
Observation	154388	59065
P-value of χ_2	0.000	0.000
Pseudo R^2	0.0124	0.0012
Log likelihood	-78689.981	-40310.395

Panel B. Staggered difference-in-differences regression based on matching sample		
	$\Delta P_{ij,t}$ (Top 50 countries)	
	(1)	(2)
$\Delta E_{ij,t}$	0.489***	0.491***
	(15.812)	(13.873)
$\Delta E_{ij,t} * Shock_{i,t}$	0.281***	0.263***
	(9.181)	(7.426)
$Shock_{i,t}$	0.008	0.010*
	(1.561)	(1.669)
$Bitcoin_{i,t}$	0.006	-0.006
	(0.561)	(-0.571)
$\Delta Volume_{ij,t}$	-0.484***	-0.493***
	(-244.733)	(-229.745)
$\Delta GDP_{i,t}$	0.007***	0.006***
	(10.475)	(6.946)
$\Delta GDP_{j,t}$	0.009***	0.010***
	(16.772)	(16.028)
$Inflation_{i,t}$	0.006***	0.008***
	(15.773)	(13.641)
$Inflation_{j,t}$	0.003***	0.002***
	(9.680)	(4.669)
ΔWTI_t	0.000**	0.000
	(2.541)	(1.557)
$LnVIX_t$	0.017*	0.027***
	(1.862)	(2.670)

Paired FE	No	Yes
Observations	58,733	58,390
Adj. R-squared	0.513	0.567

This table reports the regression results using a propensity score matching (PSM) procedure. Panel A, Column 1, presents the results of a probit model based on the pre-matched countries in the treatment and the control groups. The dependent variable of the probit model equals one if the country belongs to the treatment group and zero if the country comes from the control group. Panel A, Column 2, presents the results of the same probit model based on the post-matched countries in the treatment and the control groups. Panel B presents the results for the staggered difference-in-differences regression based on the matched sample. Appendix A presents the detailed variable definitions. All continuous variables are winsorized at the 1% and 99% levels. The *t*-statistics are reported in parentheses *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4.7 Placebo test

Our baseline regression confirms that the development of CBDCs in exporting countries (country *i*) helps to enhance the currency invoicing power. However, the CBDC development would have a limited impact on the exchange rate pass-through if a country's currency is not the invoicing currency in international trade. Thus, we suppose the development of CBDC in the importing country may impact the international financial market, altering capital flows and the supply-demand relationship of currencies, thereby indirectly affecting the stability and pricing ability of the exporting country's currency. We conduct a placebo test by using the CBDC announcement year of the importing country as a "fake shock" to confirm that the effect identified in the baseline test is not accidental. We use the variable $Shock_{j,t}$ to represent whether the importing country *j* has developed a CBDC, with a value of 1 if yes, and 0 otherwise. Regression result, as shown in Table 3.7, indicates that the coefficient of the interaction term $\Delta E_{ij,t} * Shock_{j,t}$ is not significant, passing the placebo test.

Table 3.7 Placebo test

	$\Delta P_{ij,t}$
	Top 50 countries
$\Delta E_{ij,t}$	0.672***
	(31.131)
$\Delta E_{ij,t} * Shock_{j,t}$	0.033
	(0.303)
$Shock_{j,t}$	0.005
	(0.317)
$Bitcoin_{i,t}$	0.016***
	(2.850)
$\Delta Volume_{ij,t}$	-0.467***
	(-316.182)
$\Delta GDP_{i,t}$	0.007***
	(8.972)
$\Delta GDP_{j,t}$	0.007***
	(12.546)
$Inflation_{i,t}$	0.008***
	(17.418)
$Inflation_{j,t}$	0.002***
	(5.777)
ΔWTI_t	0.000***
	(5.623)
$LnVIX_t$	-0.048***
	(-6.649)
Paired FE	Yes
Observations	113,702
Adj. R-squared	0.505

This table reports on whether the development of CBDCs by import economies affects the use of export economies' currencies in international settlements. $Shock_{j,t}$ indicates whether the import economy has initiated CBDC development in year t, with a value of 1 if yes, and 0 otherwise. Appendix A presents the detailed variable definitions. All continuous variables are winsorized at the 1% level in each tail. The country level paired fixed effects and *t*-statistics are presented in parentheses, where *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

4.8 Further analysis

By 2023, there are seven countries in our baseline regression sample had initiated pilots for CBDCs[1]. To further explore the impact of a country's CBDC development level on its currency invoicing ability, we establish the variable $Shock\_pilot_{i,t}$, which indicates whether the country started a CBDC pilot in that year, with 1 for yes and 0 otherwise. This variable was then used to replace the CBDC shock in the baseline regression for a revaluation. The result, as shown in Table 3.8, reveals that $\Delta E_{ij,}$ and $\Delta P_{ij,t}$ are positively correlated at the 1% significance level, and the interaction term $\Delta E_{ij,t} * Shock\_pilot_{i,t}$ is significantly positive at the 1% level, consistent with the baseline regression in Table 3.3.

Furthermore, to compare with the results between Table 3.3 and Table 3.8, the coefficients of $\Delta E_{ij,}$ in Columns (1) and (2) of Table 3.8 are 0.626 and 0.643 respectively, which are higher than those in Table 3.3, where they are 0.604 and 0.594. Similarly, the coefficients of the interaction term $\Delta E_{ij,t} * Shock\_pilot_{i,t}$ Columns (1) and (2) of Table 3.8 are 0.546 and 0.375, respectively, exceeding the coefficients of the interaction term $\Delta E_{ij,t} * Shock_{i,t}$ in Table 3.3, which are 0.134 and 0.218. This further analysis suggests that CBDC pilot action has a more significant impact on enhancing the country's currency invoicing capability compared to CBDC intentions.

[1] As of 2023, the 7 countries with CBDC pilots in the top 50 are: Saudi Arabia, United Arab Emirates, China, France, Nigeria, India, and Singapore.

Table 3.8 The influence of CBDC pilots on currency pricing power in bilateral trade

	$\Delta P_{ij,t}$	$\Delta P_{ij,t}$
	(1)	(2)
$\Delta E_{ij,t}$	0.626***	0.643***
	(25.760)	(35.318)
$\Delta E_{ij,t} * Shock\_pilot_{i,t}$	0.546***	0.375***
	(3.925)	(3.798)
$Shock\_pilot_{i,t}$	0.083***	0.034**
	(4.408)	(2.563)
$Bitcoin_{i,t}$		0.011**
		(2.143)
$\Delta Volume_{ij,t}$		-0.473***
		(-366.708)
$\Delta GDP_{i,t}$		0.007***
		(12.553)
$\Delta GDP_{j,t}$		0.008***
		(18.830)
$Inflation_{i,t}$		0.008***
		(20.990)
$Inflation_{j,t}$		0.002***
		(9.012)
ΔWTI_t		0.000***
		(4.488)
$LnVIX_t$		-0.017***
		(-2.861)
Paired FE	Yes	Yes
Observations	146,315	146,315
Adj. R-squared	0.024	0.509

This table reports further discussion regarding the influence of CBDC pilots on international settlements. We use 7 countries in the top 50 which are going their CBDC pilot as our sample. $Shock\_pilot_{i,t}$ represents whether the country started a CBDC pilot in that year, with 1 for yes and 0 otherwise. Appendix A presents the detailed variable definitions. All continuous variables are winsorized at the 1% level in each tail. The country level paired fixed effects and *t*-statistics are presented in parentheses, where *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

5. Conclusion

Currently, there is no CBDCs settlement data on cross-border payments. However, our study supports our hypotheses as to how CBDCs effect currency invoicing power, exchange rate volatility, and would affect currency diversification. Our findings indicate that the development of a country's CBDC significantly strengthens the transmission of bilateral exchange rate changes between exporting country and importing country into changes in the prices of traded commodities, thereby enhancing the exporting-country's currency invoicing power. These results remain significant after a series of robustness tests. Mechanism test suggests that the development of a country's CBDC enhances the trade invoicing power of its currency by reducing exchange rate volatility, as well as increasing currency liquidity in international foreign exchange market. We further find that these effects are even stronger in countries that have piloted CBDC programs. In summary, our findings suggest that CBDCs are beginning to influence exchange rate stability and liquidity, which in turn affects the currency invoicing power. This process will commence with CBDC development and is expected to become more pronounced as their implementation progresses, which is currently just beginning to occur.

CHAPTER FOUR ESSAY THREE

Development and Implementation of e-CNY: Research on the Supply, Demand, and Infrastructure aspects of e-CNY

Abstract

This chapter studies how digitalization affects the adoption of China's central bank digital currency (e-CNY). Utilizing provincial-level panel data from 2011 to 2021, this study analyses the impacts of "Breadth of Digitalization Coverage" and "Digitalization Level" on the supply and demand dynamics of China's central bank digital currency (called e-CNY), within the framework of digitalization development. Our findings reveal an increase in digitalization correlates with a decline in the supply and demand for paper currency, highlighting that digitalization has paved the way for adopting e-CNY. Further analyses show that the penetration of smartphones and the growth of e-commerce have been instrumental in broadening digitalization coverage and the level of digitalization, indicating that the digitalization of wallets and payment scenarios has laid a solid foundation for implementing e-CNY.

Keywords: central bank digital currencies, digital currency, digitalization, digital payments, e-CNY

1. Introduction

In recent years, there has been a global surge in the exploration of Central Bank Digital Currencies (CBDCs), with 134 countries and regions actively engaged in researching or piloting their own CBDCs (Atlantic council, 2024). Simultaneously, there has been an increase in international collaborative CBDC projects, indicating a growing emphasis on interoperability in digital currency systems. Studies by institutions such as the BIS and IMF suggest that digitalization has improved transaction efficiency and motivated central banks to explore CBDCs as a response to the rise of private digital currencies (Kiff et al., 2020; Kosse & Mattei, 2023). Despite the increasing need to understand CBDCs, existing literature has provided limited evidence, primarily relying on the theoretical models of CBDCs (Allen et al., 2022; H. Wang, 2023; Xu, 2022). To the best of our knowledge, no empirical evidence has been established, mainly due to the challenges of obtaining data, as most CBDC projects are still in the research or pilot phases. The lack of empirical analysis creates significant gaps in understanding the practical implications of CBDCs.

Given that most CBDC projects are still in the research or pilot phases, direct empirical evidence remains scarce. To address this gap, this study adopts an indirect observation approach by exploring the potential relationship between the development of digitalization and the adoption of CBDC in China. The development of CBDCs is closely intertwined with the broader trend of payment system digitalization, which has led to a decreasing reliance on physical cash and a growing adoption of digital payment methods. Through this research design, the study aims to infer the possible role of

CBDC in the evolving monetary system.

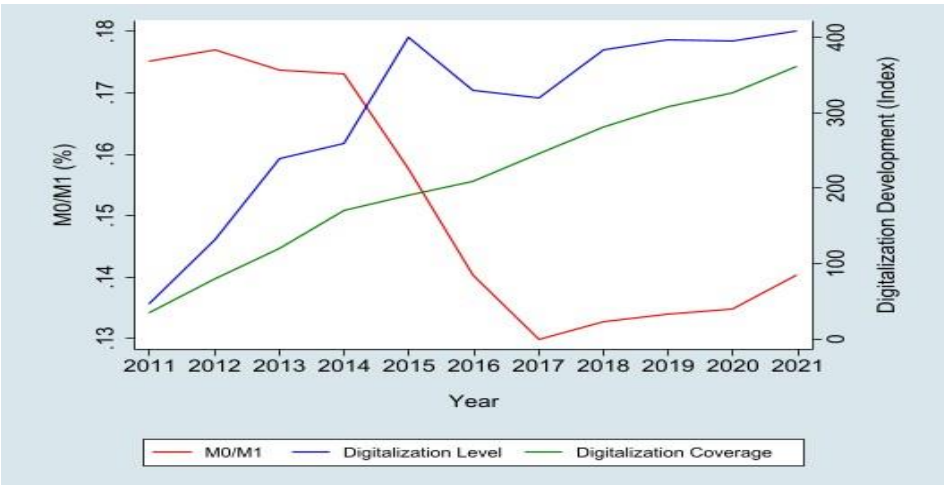
In January 2025, the U.S. issued an executive order banning the ‘digital dollar’ (Reuters, 2025), adding further to the geopolitical divide over central bank digital currencies. China provides a unique setting for studying the development and implementation of a domestic CBDC due to its distinctive socio-economic landscape and the influential role in global affairs. Typically, there are two potential approaches for a country to develop an innovative digital currency: gradually transitioning from paper currency to electronic forms of storage and then to digital payments or shifting directly from paper currency to digital currency. China is following the first approach, moving from the advanced electronic payment systems to digital currency payments, which allows for a smooth transition and infrastructure development. The further reasons of focusing China are as follows.

First, China has advanced digital infrastructure and widespread adoption of digital payment. According to the "Overall Operation of the Payment System in 2022" released by the People's Bank of China, by the end of 2022, the scale of mobile payment users in China reached approximately 904 million, accounting for 86.5% of the total number of internet users. Given its large population of electronic payment users and advanced electronic payment infrastructure, China has the suitable conditions to popularize digital currency locally (Liu et al., 2024).

Second, China is one of the first major economies to launch CBDC pilot with significant progress in the recent years. Since initiating CBDC research in 2014, China has progressively expanded e-CNY trials to 26 regions across 17 provinces and cities, with total transaction volume reaching 7 trillion Chinese yuan by June 2024 (Atlantic council, 2024).

Third, China’s well-developed mobile payment system, dominated by platforms such as Alipay and WeChat Payment, has established a strong framework for e-CNY’s implementation (Allen et al., 2022). This sets China apart from countries without advanced mobile payment infrastructures and could serve as a "shortcut" in the e-CNY process. As illustrated in Figure 4.1, since the rise of e-commerce and widespread use of Alipay in 2014, physical cash usage has dropped significantly, along with a notable decline in the M0 to M1 ratio, despite continued growth in China’s narrow money supply. This trend suggests that digitalization development could have reduced the share of physical cash in total money circulating in China.

Figure 4.1 Relationship between digitalization development and the ratio of physical currency in China



This figure illustrates the inverse relationship between China’s digitalization development—measured by both digitalization coverage and level—and the proportion of physical cash, as indicated by the declining M0/M1 ratio. The Digital Financial Inclusion Index, calculated as national averages across 31 provinces by Peking University, represents digitalization progress. (Source: China National Bureau of Statistics, Institute of Digital Finance of Peking University)

As China's e-CNY remains in the trial stage, direct empirical data are unavailable. This study examines how the development of digitation affects the use of physical CNY to infer insights into the future development of e-CNY. First, this study examines the influence of digitation development on physical currency and reveals shifts in payment habits, indicating public acceptance of cashless transactions—an essential condition for e-CNY adoption. Second, CBDC implementation heavily relies on a well-developed digital infrastructure, including payment networks, mobile devices, and cybersecurity (Adhikary et al., 2021), which are essential for operating e-CNY. This study uses provincial-level panel data from 31 Chinese provinces (2011–2021) to assess how the breadth and depth of digitalization—measured by the digitalization coverage and digitalization level, respectively—affect the supply and demand for physical cash. M0 and cash withdrawal are used as direct proxies of the supply and demand of physical CNY (inverse proxies for the supply and demand of e-CNY), respectively. M0 and cash withdrawal are used as direct proxies of the supply and demand of physical CNY (inverse proxies for the supply and demand of e-CNY), respectively. We further analyze the role of digital infrastructure, such as mobile phones and e-commerce, in shaping China's digital payment ecosystem. The results show that the development of digitalization significantly reduces both the supply and demand of physical currency, suggesting a potential shift towards e-CNY. Moreover, mobile payment devices, represented by smartphones, and the growth of e-commerce are crucial drivers of digitalization, which would support e-CNY's future implementation.

The findings lead to the following conclusive statements and implications. First, the digitalization of physical wallets, driven by widespread smartphone adoption, facilitates currency's digitalization. As portable and intelligent carriers of digital wallets, smartphones bridge the "last mile" of digitalization, providing individuals with ubiquitous platforms to store, manage, and transact with e-CNY. Second, the expansion of digital payment scenarios, particularly through the growth of e-commerce, strengthens the foundation for e-CNY adoption. By enriching the digital transaction ecosystem, this shift fosters new digital payment habits and reduces reliance on physical currency. Based on the findings, the digitation of Chinese Yuan is both conditional and inevitable, though overcoming developmental challenges will take time. Policymakers must ensure financial inclusivity while prioritizing privacy protection and security, especially in digital wallet design. A full transition to a digitized fiat currency system will also require comprehensive legal and regulatory reforms to safeguard the public's right to use physical legal tender and mitigate digital inequality, particularly for those unfamiliar with technology or in regions lacking adequate digital infrastructure. Additionally, commercial banks must adapt to CBDC by embracing technological innovation and shifting from traditional to technology-driven models to remain competitive in an increasingly digital financial environment.

Our study makes the following contributions. First, this study enriches the existing literature on empirical investigation on CBDC, where empirical analyses are notably scarce. The existing studies provide only theoretical evidence on the framework of CBDC, almost certainly due to data limitation (Allen et al., 2022; H. Wang, 2023; Xu, 2022). By creatively employing supply and demand of physical CNY as the inverse indicators for e-CNY, we provide the first piece of empirical evidence to demonstrate that the development of digitalization significantly promotes the adoption of CBDC in China. Second, our study contributes to the expanding body of knowledge on CBDCs, focusing on China's e-CNY. Considering China's digital infrastructure is state-owned, in contrast to western model of privatization, our analysis provides an examination of the infrastructural factors influencing digitalization coverage and level in China. This offers insights that could assist in the development and implementation of similar digital currencies globally. Finally, by examining the relationship between digitalization development and paper currency, we aim to forecast the potential supply and demand for the upcoming e-CNY, which may offer valuable insights for policymakers and financial institutions navigating the new terrain of monetary digitalization for countries with similar electronic payment ecosystems.

The remainder of this chapter is structured as follows. Section 2 reviews the relevant literature review. Section 3 develops the hypotheses regarding three aspects of e-CNY’s supply, demand, and digital infrastructure. Section 4 describes data and variable construction, as well as the methodologies employed. Section 5 presents the experimental findings. Section 6 discuss the results and provides conclusions and policy implications.

2. Literature review

2.1 Distinguishing CBDC, physical currency, and electronic payment

CBDCs, electronic payments, mobile payments, and traditional paper currency now coexist in a complex ecosystem, with each element influencing and shaping the others. Demirguc-Kunt et al. (2018) point out that electronic payment systems can improve access to financial services, reduce transaction costs, and facilitate remittance flows in developing countries. Some scholars argue that the increased convenience and efficiency of digital payments could lead to a 'cashless society' (Bech et al., 2018). The introduction of electronic payments has implications for reducing the traditional M0 in China (Qin, 2017), as more people use digital platforms such as Alipay and Tenpay to make payments.

CBDCs are designed to leverage digital technologies to improve the efficiency and inclusivity of financial systems (Chen & Siklos, 2022). The Atlantic Council suggests that CBDCs may reduce the demand for cash (Chiu & Davoodalhosseini, 2023). This transition is linked to the efficiency and broader adoption of CBDCs, which may offer benefits such as increased consumption and welfare, while potentially reducing reliance on physical cash in the economy (Chiu & Davoodalhosseini, 2023). E-CNY may grow rapidly in the future as the PBoC expands its pilot programs and promotes its usage domestically and internationally. However, without an interest rate, e-CNY may also increase the demand for deposits, as people may need to exchange e-CNY for bank deposits to earn interest or access other financial services.

To summarize, the dynamics among paper currency, electronic payments based on traditional currency, and CBDC transactions reflect shifts in liquidity, accessibility, and the balance between physical currency demand and bank deposits.

2.2 CBDCs conceptual framework

CBDCs, digital counterparts to fiat currencies, are designed to digitize and modernize financial systems through enhanced efficiency and broader financial inclusion (Bank for International Settlements et al., 2020). Unlike decentralized cryptocurrencies, CBDCs are regulated by central authorities (Barrdear & Kumhof, 2022). They vary in design, being retail or wholesale, and either account-based or token-based (Chen & Siklos, 2022), depending on a country's specific circumstances (Mancini-Griffoli et al., 2018). Retail CBDCs aim to improve financial inclusion in regions with limited banking access. Moreover, CBDCs feature potential real-time transactions, traceability, and programmability (Böhme et al., 2015), as well as combine the convenience of digital transactions with the security of government-issued currencies.

E-CNY, launched for retail use (Yao, 2018), is China's digital currency effort to enhance the Chinese yuan by gradually replacing physical cash and combating counterfeiting (Qian, 2019). It operates as cash in circulation, making it a central bank liability that earns no interest, with its wallet separate from bank accounts to maintain monetary and financial stability (Mu, 2022). Unlike decentralized cryptocurrencies, e-CNY follows a centralized, two-tier distribution system involving the PBoC and commercial banks, using blockchain as a foundational framework (refer to Figure 4.2). Notably, e-CNY supports offline transactions and controllable anonymity, allowing users to transfer e-CNY without a bank account or network, while still enabling traceability by the central bank to balance privacy with regulation.

Currently, e-CNY has developed a relatively comprehensive theoretical framework. The PBoC’s report (People's Bank of China, 2020) and white papers (People's Bank of China, 2021) introduce e-CNY's objectives, features, aims, legal framework, progress, and achievementsts, highlighting its role in improving payment efficiency, financial inclusion, and financial innovation. Unique features include "double offline payment" and account independence, allowing transfers without a bank account or network (refer to feature details in Appendix H).

Figure 4.2 Two-tier distribution system of e-CNY

This figure illustrates e-CNY’s two-tier distribution structure. The first tier consists of the Central Bank (PBoC), while the second tier includes commercial banks and non-bank institutions, such as digital payment platforms (e.g., JD, Meituan, DIDI) and telecom operators (e.g., China Mobile, China Unicom, China Telecom). Under this framework, the central bank issues e-CNY to 'Digital Money Bank Storehouses' held by these institutions. In return, they must deposit a corresponding reserve into the central bank’s 'e-CNY Issuing Storehouse' as issuance capital. These institutions then distribute the regulated e-CNY to the public.

2.3 Infrastructures for CBDC implementation

We aim to explore the future application scenarios and impact of e-CNY through the development of digital payments. The advancement of e-CNY not only depends on the technological innovations of CBDC, but its widespread adoption also relies on a broadly accessible digital payment infrastructure and well-established user habits in using digital payments.

The widespread adoption of smartphones has provided a solid user base for the rapid expansion of convenient digital payments. According to Mallat (2007), the portability and constant availability of smartphones significantly increase users' willingness to engage in mobile payments. Meanwhile, Dahlberg et al. (2015) pointed out that advancements in smartphone technology, such as fingerprint recognition, facial recognition, and NFC technology, offer users a more secure and convenient payment experience. These technological developments and the cultivation of user habits have laid a solid foundation for the promotion of e-CNY. From a technological perspective, e-CNY will inherit the advantages of existing mobile payments in terms of convenience while further enhancing its usability in offline environments through features like offline payments and dual offline technology (Humbani & Wiese, 2019).

Central bank digital currency represents not merely a byproduct of technological progress but also a shift in the future forms of currency and methods of transaction (White et al., 2020). Dahlberg et al. (2015) highlight the increased adoption of mobile payments with the proliferation of smartphones, the development of mobile applications enabling secure transactions, and payment technology such as contactless near-field communication (NFC). In terms of mechanism design, e-CNY adheres to principles of "small-amount anonymity and large-amount traceability" along with "loose coupling between wallets and accounts," effectively striking a balance between individual privacy protection and public safety (Xu, 2022). This design not only meets the needs of high-frequency payment scenarios in major cities but also provides a more stable payment solution in special situations such as remote areas and post-disaster recovery (Humbani & Wiese, 2019).

The widespread adoption of e-CNY relies not only on the prevalence of smartphone usage among consumers but also on its application and development in the business environment. With the rise of e-commerce, companies are increasingly adopting digital transaction methods to enhance operational efficiency, reduce costs, and expand their markets (Yang et al., 2023). Through digital management systems and e-commerce platforms, businesses can better integrate their supply chains and optimize business processes, providing technological support and operational convenience for the future application of e-CNY on the corporate side. E-commerce platforms not only offer efficient online transaction channels but also enhance overall business operations through digital management systems (Yang et al., 2023). The introduction of e-CNY aligns with this digital trend, offering businesses a more convenient and secure payment method. The widespread use of e-commerce platforms has created a favorable business environment for the application of digital currencies, enabling real-time settlement and cross-border payments, thereby reducing financial costs and transaction risks. As businesses increasingly rely on digital tools, the introduction of e-CNY may help companies achieve more efficient payment integration, reducing settlement times and cross-border payment costs. Allen et al. (2022) suggest that e-CNY could support more complex commercial transactions and financial services through technologies like smart contracts in the future, further enhancing business efficiency and competitiveness.

According to the announcement of PBoC, serving as a carrier and medium for digital currency payments, e-CNY digital wallet [1] is classified into four distinct categories based on the level of customer identity verification and corresponding transaction limits (refer to Appendix I).

[1] The SIM card-based hardware wallet for e-CNY provides an innovative approach to streamline digital payments. It ties the e-CNY software wallet to a specially issued "super" SIM card by telecom operators. Upon logging into the e-CNY app and activating the SIM card hardware wallet function, users can make payments using their phone's NFC capability. A simple "tap" or "touch" processes the e-CNY transactions.

3. Hypothesis development

The rapid growth of digital payments in China reflects a shift in consumer and business preferences away from cash-based transactions (Xia et al., 2023). Despite the advantages of digital payments and CBDCs, paper currency still plays a significant role. This will continue until a fully digital economy ecosystem is established, at which point all physical currency will be completely replaced by digital alternatives. However, traditional paper currency, as the conventional medium of exchange, is increasingly seen as inadequate to meet the rising demand for circulation speed and efficiency. In this context, digital currency would offer a viable alternative to paper currency, providing a more effective solution for modern society's needs regarding the velocity and efficiency of currency circulation (Chen & Siklos, 2022).

In this chapter, we argue that the digitalization development in China has paved the way for the emergence of e-CNY. To explore the conditions for implementing e-CNY, we structure our research hypotheses around three core dimensions: e-CNY supply, e-CNY demand, and financial infrastructure. However, the unavailability of e-CNY data poses a challenge for conducting a comprehensive analysis. Consequently, we propose using an inverse indicator, physical currency, to infer potential implications for e-CNY adoption.

3.1 Influence of digitalization development on e-CNY supply

The velocity of money essentially refers to the rate at which money changes hands in an economy. According to Irving Fisher's Theory (Fisher, 1930), articulated through the equation MV=PT, there is an inverse relationship between the money supply (M) and the velocity of money (V), assuming constant prices (P) and transaction volume (T). Therefore, in the context of increasingly prevalent digital transactions, it leads to a higher velocity of money.

The development of digital payments in China, particularly the widespread use of mobile payments, may reduce the demand for physical currency. The growth of third-party payment platforms can enhance the convenience and efficiency of transactions, causing cash to gradually lose its status as the primary payment tool in daily life (Xia et al., 2023). Moreover, the proliferation of digital payments may also lower the costs associated with cash management. Cash management involves processes such as printing, transportation, storage, and distribution, all of which are expensive, especially in remote areas (Tee & Ong, 2016). The advancement of digital payments has effectively reduced the frequency of cash usage, thereby decreasing the demand and costs associated with cash management, prompting the central bank to be more cautious in the supply of physical currency (Brown et al., 2022). The Chinese government has also actively promoted the use of mobile payments in public services, such as public transportation, healthcare, and education, further reducing reliance on physical currency (Dong et al., 2023). Given the theoretical framework outlined above, we propose the following hypothesis:

Hypothesis 1. *The development of digitalization leads central bank to reduce the supply of paper currency, inferring the increased incentive in promoting e-CNY.*

This dynamic indicates that with the advancement of digitalization, the government reduces the supply of physical currency. Such digitalization has primed the economic landscape for e-CNY, potentially motivating the government to further adjust the supply of traditional paper currency downwards.

3.2 Influence of digitalization development on e-CNY demand

Keynes (1937) proposes three motives for holding money: the transactions motive, the precautionary motive, and the speculative motive. The rise of digital payments, known for speed, convenience, and accessibility, has started to overshadow traditional cash transactions, shifting paper currency dynamics (Ching & Hayashi, 2010). With digital platforms becoming the main transactional channels (Huang et al., 2020; Yang & Zhou, 2022), there's a noticeable decline in physical currency demand. The transactions motive for cash is diminishing, hinting at reduced demand. Digital expansion suggests moving towards a less cash-reliant society, although not entirely eliminating cash usage across all demographics and scenarios (Bech et al., 2018). Khiaonarong and Humphrey (2022) find that the increasing popularity of digital payments has a negative impact on the demand, especially in developed countries. China's shift from physical currency to digital payments, driven by mobile platforms like Alipay and WeChat Pay, has made mobile payments the dominant transaction method, surpassing cash usage in many regions (Huang et al., 2020). This suggests an inverse relationship between digitalization and cash demand inverse relationship. Building upon these considerations, we posit the hypothesis:

Hypothesis 2. *The development of digitalization reduces reliance on paper currency, inferring the increased demand of e-CNY.*

This transition underscores a growing societal dependency on digital forms of money, indicating that the reduction in paper currency is not merely a consequence of digitalization but also a testament to the increasing preference for and reliance on digital currency solutions.[1]

3.3 Influence of infrastructure on digitalization development

The convenient mobile payment system has led to a significant decrease in people's demand for paper currency. From the perspective of infrastructure, one of the fundamental reasons for this shift is the widespread availability of smartphones, a primary factor impacting digital coverage. With increasing smartphone penetration, a multitude of cashless consumption scenarios, such as online shopping platforms and digital supermarkets, have been made readily accessible. These platforms can be easily integrated into mobile payment terminals, removing the limitations of traditional payment scenarios. Users are now able to engage in transactions anytime, anywhere, with the simplicity of a few taps on a smartphone screen. This convenience has resulted in a surge in the number of mobile payment system users, further reducing the demand for physical cash.

Furthermore, e-commerce growth contributes to increased digitalization (Molla & Licker, 2005). Since the advent of e-commerce, the Chinese government has been vigorously promoting the development of digital infrastructure, including the widespread use of mobile payment systems and electronic payment scenarios. These systems, as a key component of digital financial infrastructure, have played a critical

1 Alternative opinion: inclusive finance aims to make financial services accessible to all, regardless of income or social status. The growth of digital technologies has played a pivotal role in promoting financial inclusion, facilitating the creation of platforms and services that make banking more accessible to underprivileged and rural populations. This has led to a broadening of the money supply (M1), as more individuals are able to access and utilize financial services.

role in providing financial services to populations previously underserved by traditional banking, particularly in rural areas. This increase in access to financial services has led to a shift in payment preferences, with more people opting for mobile payment systems over physical cash. Therefore, we posit the following hypotheses:

Hypothesis 3. *The use of mobile phone payment device plays a positive role in improving digitalization coverage level.*

Hypothesis 4. *The e-commerce system has a positive impact on the digitalization level.*

4. Research design

4.1 Data and sample

The data collection process for this study focuses on estimating the impact of digitalization on both e-CNY money supply and demand, while also exploring the role of digital infrastructure in facilitating the development of digitalization.

Since e-CNY remains in the pilot stage in China, direct data observations are not available. Due to this data limitation, we employ the supply and demand of physical cash as inverse indicators for the demand and supply of e-CNY. Given that e-CNY is intended to replace physical money in circulation, the empirical analyses conducted using these inverse indicators should provide meaningful inferences about the development and implementation of e-CNY. Both e-CNY and physical currency are legal tender issued by the People's Bank of China (PBoC), with e-CNY specifically designed to serve as a substitute for M0, the most liquid component of the currency. Accordingly, we use M0 as the realized supply for physical currency, following the approach of Berger and Bouwman (2013). The evolving digital finance is captured through an analysis of the digital payment ecosystem. As detailed in Appendix D, the "Breadth of Coverage" (renamed as "Digitalization Coverage" in this study) captures the extent to which digital financial services, particularly Alipay, have penetrated the population.

We conduct provincial level analysis using a sample of 31 Chinese provinces from 2011 to 2021. This coverage allows us to have a comprehensive understanding of the monetary dynamics across different Chinese provinces, providing a holistic view of the impact of digitalization on e-CNY. To account for the significant socioeconomic and technological disparities among provinces in China, we have controlled for provincial-level fixed effects in the baseline regression. The traditional physical cash data is sourced from the China National Bureau of Statistics People's Bank of China's official website. Macroeconomic data, which includes variables such as GDP, population, education level, and age, is gathered from the China National Bureau of Statistics. The collection of these macroeconomic indicators will enable the study to consider the different demographic and economic characteristics across provinces. The "Breadth of Coverage" and "Level of Digitalization" are sub-indicators within PKU-DFIIC and derived from the Peking University Digital Financial Inclusion Index (PKU-DFIIC).

4.2 Variables construction

4.2.1 Measurement of e-CNY supply

Since the data of e-CNY is not available, we use the supply of physical cash (M0) as an indirect proxy, given that e-CNY is expected to replace physical currency in circulation. A decrease in the physical currency supply implies an increase in the supply of e-CNY, and vice versa.

The rise of electronic payments, notably mobile payments, has blurred the boundaries between various forms of money, prompting economists to reassess traditional monetary definitions and measurement frameworks. Users can exchange their cash to savings and convert the forms of money at any time since electronic money is a virtual form on the network. This would reduce the liquidity gap between different forms of money (Qin, 2017). Based on Cohen (2001), M0—comprising banknotes and coins directly issued by state authorities—serves as an indicator for assessing changes in the supply of physical currency. To estimate the potential supply of e-CNY, we employ the M0-to-GDP ratio (M0/GDP) as a proxy for physical currency supply and use it to conduct a reverse projection of e-CNY supply. This ratio is calculated by dividing the nominal M0 for each province by the corresponding provincial GDP. It captures the supply dynamics of money by considering the significant socioeconomic disparities between provinces in China. Because The M0/GDP ratio includes not only physical currency but also demand deposits and other liquid assets, and the influence of prevalent mobile payments extends beyond cash, affecting other liquid assets incorporated into M0 (Bagnall et al., 2014). Furthermore, to ensure comparability across time, provinces, and inflation effects, we deflate nominal M0 using the GDP price index to derive real M0.

Since M0 data is only available at the national level, we estimate the provincial level M0 aggregates using national M0 time series data and bank branch distribution panel data ($BBes$). We assume that M0 is allocated in proportion to the market share of bank branches, which serve as key channels for issuing and recycling banknotes. In other words, provinces with greater number of bank branches should have greater M0 supply allocated from the central bank. Specifically, in step 1, we firstly collect the national M0 time-series data (2010-2021) from China State Statistics Bureau. In step 2, Equation 1 calculates the market share of bank branches. In each year *t* we divide the number of bank branches in each province *i* by the total number of bank branches across the country. In step 3, Equation 2 estimates the panel data of the M0 across 31 provinces in China during the period of 2010 to 2021.

Equation 1:

$$Market\ Share\ of\ BBes_{i,t} = Number\ of\ BBes_{i,t} / Total\ number\ of\ BBes_{National,t}$$

Equation 2:

$$MS\_M0_{i,j} = M0_{National,t} * Market\ Share\ of\ BBes_{i,t}$$

4.2.2 Measurement of e-CNY demand

In the absence of a direct measurement for e-CNY, we use physical currency usage as a proxy for cash demand, serving as an inverse predictor of future e-CNY demand. Annual nationwide cash withdrawal data is obtained from the People's Bank of China's reports. Following David et al. (2016), to estimate provincial cash withdrawals, we apply a method similar to our M0 estimation, i.e. using national cash withdrawal data and the market share of bank branches in each province to estimate the provincial cash withdrawal data. Since money demand mainly stems from individual liquidity needs, we use the ratio of cash withdrawals to GDP (*CashWithdrawal/GDP*) as a clear-cut indicator of e-CNY demand in our main regression. Even in a digitizing economy where mobile payments reduce the need for physical cash, the *CashWithdrawal/GDP* ratio helps quantify this transition. The lower the proportion, the lower the demand of physical cash, and hence the higher the demand of e-CNY. Our methodology for estimating each province's M0 in Equation 3 adopts a similar approach to the one used for M0 as detailed in section 2 (refer to the explanation provided by Equation 1 for detailed calculation procedures).

Equation 3:

$$MD\_CashWithdrawal_{\_i,t} = CashWithdrawal_{National,t} * Market\ Share\ of\ BBs_{i,t}$$

4.2.3 Measurements of digitalization development

We employ *Digitalization_coverage* to measure the breadth of digitalization. This metric comprises three indicators: the "Account Coverage Rate" (Alipay accounts per 10,000 people), the proportion of users linking bank cards to Alipay, and the average number of linked bank cards per Alipay account. These indicators highlight the interoperability between traditional banking and digital payment platforms.

The variable *Digitalization Level* assesses the convenience and affordability of digital financial services across dimensions such as “Mobility”, “Affordability”, “Credit”, and “Convenience”. The Mobility dimension, represented by the proportion of mobile payment transactions and total transaction amounts, reflects the transition from cash to digital payments. A higher value indicates a stronger preference for mobile payments, indirectly influencing physical cash demand and supply. Variable definitions are detailed in Appendix J.

4.3 Model specification

To examine the influence of digitalization on the demand and supply of e-CNY, we employ the following regression models [1]-[2].

$$MS_{it} = \alpha_{it} + \alpha_1 DIndex_{it} + \alpha_2 Control_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad [1]$$

$$MD_{it} = \beta_{it} + \beta_1 DIndex_{it} + \beta_2 Control_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad [2]$$

Where MS_{it} denotes physical currency supply in province *i* in year *t*, measured as the ratio of M0 to GDP (M0/GDP). MD_{it} denotes physical currency demand in province *i* in year *t,* measured as the ratio of cash withdrawal to GDP (Cash withdrawal/GDP). $Control_{it}$ represents a set of control variables, including $Population_{i,t}$, $GDPG_{i,t}$, $OADR_{i,t}$, $Education_{i,t}$, and $CPI_{i,t}$. Following Barro and Lee (2013), the education indicator is calculated using a weighted average method[1]. μ_i and δ_t are provincial fixed effect and year fixed effect, respectively.

To further investigate the factors contributing to digitalization development, we employ model [3] to assess the determinants of digitalization coverage and digitalization level. Specifically, we test whether mobile phone penetration ($Mobile\ Phone_{i,t}$) and e-commerce activity ($E\text{-}commerce_{i,t}$) serve as the foundational drivers for

[1] The formula is given as follows: Education = [(No schooling population * 1 year) + (Primary school population * 6 years) + (Junior high school population * 9 years) + (Senior high school population * 12 years) + (Undergraduate population * 16 years) + (Master population * 19 years)] / Total population.

digitalization progression.

$$DIndex_{it} = \gamma_{it} + \gamma_1 FI_{it} + \gamma_2 Control_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad [3]$$

Where $DIndex_{it}$ captures digitalization's development, encompassing both the digitalization coverage index and digitalization level index for province *i* in year *t*. FI_{it} represents foundational drivers including $Mobile\ Phone_{i,t}$ and $E\text{-}commerce_{i,t}$. Same set of control variables is included in this model.

5. Empirical analysis

Given China's economic size and large population, along with its well-developed financial infrastructure and widespread adoption of cashless payment systems, the significant demand for currency's electronic payment provides a favorable environment and lays good conditions to e-CNY adoption. This section delves into empirical findings and discussions. By examining the relationship between the supply and demand of physical currency and the digitalization development, we hope to provide insights into the practicality and prerequisites for e-CNY's implementation.

5.1 Descriptive statistics

We begin our analysis by reporting the summary statistics for the variables used in this study in Table 4.1. The mean values of supply and demand of physical cash are 0.108 and 1.016, and their ranges are 0.016-0.255 and 0.055-2.768 respectively. The mean value for *Digitalization Level* is 3.008, with a standard deviation of 1.169, while *Dgitalization Coverage* has a mean value of 2.116 and a standard deviation of 1.039. These preliminary results indicate demonstrate sizeable variations in the digitalization coverage and level across different regions and time periods, enabling a rigorous regression analysis. *Mobile Phone* penetration rate shows a wide range of adoption rates, with a mean value of 1.006 and a standard deviation of 0.248. *E-commerce* activity also varies considerably across provinces, with a mean value of 1.089 and a standard deviation of 1.925[1].

[1] VIF tests are also conducted but results are not reported due to limited space. The tests show that all explanatory variables have VIF values do not exceed 5, further confirming the validity of our regression models.

Table 4.1 Descriptive statistics

Variables	Observation	Mean	Standard deviation	Minimum	Maximum
MS_M0	341	0.108	0.041	0.016	0.255
MD_CashWithdrawal	341	1.016	0.537	0.055	2.768
Digitalization_Coverage	341	2.116	1.039	0.020	4.334
Digitalization_Level	341	3.008	1.169	0.076	4.622
Mobile_Phone	341	1.006	0.248	0.520	1.890
E-commerce	279	1.089	1.925	0.0221	14.271
Population	341	3.525	0.842	1.128	4.843
GDPG	341	0.099	0.052	-0.053	0.267
OADR	341	10.695	2.774	4.824	18.800
Education	341	9.166	1.121	4.220	12.680
CPI	341	4.628	0.012	4.606	4.667

This table provides the descriptive statistics for the variables used in the study. The sample includes 31 provinces in China from 2011 to 2021. Comprehensive definitions of the variables are detailed in Appendix J.

5.2 Correlation matrix

Table 4.2 reports the correlation matrix for the main variables used in our analysis. The significance levels are also shown in the table to indicate whether the correlations are statistically significant at the 0.01, 0.05, and 0.10 levels. The absolute values of correlation coefficients between other variables are relatively low, indicating that there is no serious multicollinearity problem in our study.

Table 4.2 Correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) *Digitalization_Coverage*	1								
(2) *Digitalization _Level*	0.870***	1							
(3) *Mobile_Phone*	0.680***	0.461***	1						
(4) *E-commerce*	0.449***	0.271***	0.727***	1					
(5) *Population*	0.065	0.032	-0.069	-0.057	1				
(6) *GDPG*	-0.432***	-0.573***	-0.297***	-0.024	-0.074	1			
(7) *OADR*	0.586***	0.473***	0.321***	0.287***	0.431***	-0.273***	1		
(8) *Education*	0.392***	0.196***	0.619***	0.637***	0.237***	-0.263***	0.455***	1	
(9) *CPI*	-0.603***	-0.721***	-0.289***	-0.036	-0.058	0.485***	-0.322***	-0.147***	1

This table presents the correlation matrix for the variables in the analysis. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. All variables are defined in Appendix J.

5.3 The impact of digitalization development on e-CNY supply

Table 4.3 presents the regression results based on Equation [1], exploring the contemporaneous impact of digitalization at time *t* on the supply of physical currency at time *t*. Columns (1) and (3) show that the coefficients of *Digitalization_Coverage* and *Digitalization_Level* are negative and significant coefficients (-0.066 and -0.044), confirming that that higher digitalization reduces physical currency supply, confirming Hypothesis 1. This finding corroborates our theoretical proposition that the proliferation of digitalization within a region reduces reliance on physical currency, as individuals and businesses increasingly adopt digital payment methods and become less dependent on cash for transactions. We further examine how digitalization at current time *t* predicts future supply of physical currency at time *t+1* and present the results in Columns (2) and (4). We find that the impact of *Digitalization_Coverage* and *Digitalization_Level* on money supply weakens or disappears at time *t+1*.

The temporal dynamics revealed in these findings highlight the short-lived impact of digitalization on the supply of physical currency. These findings are not unexpected. While digitalization can affect the money supply in the short term, its longer-term impact remains limited, as money supply policies are directly controlled and regulated by the central banks.

Table 4.3 The influence of digitalization development on e-CNY supply

Variables	*MS_M0*	*F.MS_M0*	*MS_M0*	*F.MS_M0*
	(1)	(2)	(3)	(4)
Digitalization_Coverage	-0.066***	-0.045**		
	(-3.673)	(-2.286)		
Digitalization_Level			-0.044**	-0.029
			(-2.194)	(-1.482)
Population	-0.008	-0.047	-0.023	-0.079**
	(-0.220)	(-1.166)	(-0.628)	(-2.070)
GDPG	0.012	0.004	0.011	0.012
	(0.378)	(0.106)	(0.336)	(0.317)
OADR	0.003**	0.002	0.004***	0.002*
	(2.543)	(1.558)	(3.317)	(1.835)
Education	0.005	-0.004	0.004	-0.005
	(1.017)	(-0.821)	(0.862)	(-0.888)
CPI	0.030	-0.116	0.090	-0.090
	(0.136)	(-0.505)	(0.397)	(-0.389)
Constant	-0.101	0.858	-0.291	0.835
	(-0.096)	(0.795)	(-0.271)	(0.763)
Observations	341	310	341	310
Adj. R-squared	0.868	0.873	0.864	0.871
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

This table presents the baseline result of the impact of the digital coverage and digital level on physical currency supply. Columns (1) and (3) show the results of current period. Columns (2) and (4) presents the regression for physical currency supply in *t+1* period. *t*-statistics are presented in parentheses, where *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

5.4 The impact of digitalization development on e-CNY demand

The regression results presented in Table 4.4 show a substantial decline in physical cash usage represented by *CashWithdrawal/GDP* due to the increasing digitalization, confirming Hypotheses 2. As shown in columns (1) and (3), both *Digitalization_Coverage* and *Digitalization_Level* reduce the immediate demand for physical cash, with stronger effect associated with *Digitalization_Coverage.*

In columns (2) and (4), we conduct a one-period forward measure of monetary demand (*F.MD_ CashWithdrawal)* to assess the influence of digitalization on money demand at time *t+1*. The results demonstrate that both *Digitalization_Coverage* and *Digitalization_Level* retain statistically significant, with *Digitalization_Coverage* consistently demonstrating stronger effect. Since *Digitalization_Coverage* captures the extent to which individuals rely on electronic payment method (e.g. Alipay), our results highlight the more prominent role of advanced payment technologies in driving the transition away from physical cash. This finding reinforces that China's widespread digitization provides a strong foundation for e-CNY's implementation.

Results of control variables are generally consistent with Table 4.3, where *OADR* (old population ratio) positively correlates with cash demand, reflecting greater reliance on physical cash among older demographics. In addition, we find that *Population* negatively affects currency demand. As electronic payments become more cost-efficient in regions with larger populations, the transition from cash to digital payments becomes more pronounced and significant.

Table 4.4 The influence of digitalization development on e-CNY demand

Variables	*MD_ CashWithdrawal*	*F.MD_ CashWithdrawal*	*MD_ CashWithdrawal*	*F.MD_ CashWithdrawal*
	(1)	(2)	(3)	(4)
Digitalization_Coverage	-0.625**	-0.869***		
	(-2.173)	(-2.790)		
Digitalization_Level			-0.013**	-0.010*
			(-2.183)	(-1.689)
Population	-0.038	-0.065	-0.053	-0.081*
	(-0.132)	(-0.427)	(-0.335)	(-1.896)
GDPG	-0.551	-0.879**	-0.384	-0.769**
	(-1.512)	(-2.174)	(-1.135)	(-2.130)
OADR	0.073***	0.051**	0.056***	0.031
	(3.696)	(2.556)	(2.739)	(1.531)
Education	0.025	-0.173**	0.037	-0.161**
	(0.305)	(-2.146)	(0.451)	(-2.030)
CPI	3.464	5.682	2.565	4.921
	(0.968)	(1.586)	(0.721)	(1.399)
Constant	-24.467	-32.081*	-17.536	-24.937
	(-1.453)	(-1.895)	(-1.044)	(-1.498)
Observations	341	310	341	310
Adj. R-squared	0.806	0.815	0.809	0.822
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

This table presents the baseline result of the impact of the digital coverage and digital level on physical currency demand. Columns (1) and (3) show the results of current period. Column (2) and (4) presents the regression for paper currency demand in *t+1* period. *t*-statistics are presented in parentheses, where *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

5.5 Infrastructure analysis for foundation of e-CNY digitalization

In our previous analyses to test Hypotheses 3 and 4, we have demonstrated that digitalization significantly reduces the reliance on physical currency from both supply and demand perspectives. These findings suggest that digitalization can play a prominent role in promoting e-CNY as a replacement of physical cash in circulation. We next investigate the key factors contributing to the digitalization progression in China and report the results in Table 4.5 and Table 4.6.

Panel A of Table 4.5 reveals a positive association between the use of *Mobile Phone* and *Digitalization_Coverage*, supporting Hypothesis 3. This indicates that widespread mobile phone penetration significantly enhances digital coverage across provinces. As shown in Columns (1) and (2) of Panel A, this effect persists when the forward measure of *Digitalization_Coverage* is used at subsequent period $t+1$, but the effect gradually weakens slightly. Panel B shows *E-commerce*'s impact on *Digitalization_Coverage* but reveals no significant relationship.

In Panel A of Table 4.6, we find that *E-commerce* significantly enhances *Digitalization_Level*, indicating that e-commerce development boosts the digitalization capability. This impact remains significant in subsequent period ($t+1$). However, *Mobile Phone* appears to have no significant impact on *Digitalization_Level* as shown in Panel B.

Our results suggest that different infrastructure prerequisites are required for different aspects of digitalization: mobile phone penetration is essential for expanding the breadth of digitalization, while e-commerce plays a key role in improving its depth and sophistication.

Table 4.5 The influence of infrastructure on digitalization coverage

Panel A. Mobile phone

Variables	*Digitalization_Coverage*	*F. Digitalization_Coverage*
	(1)	(2)
Mobile Phone	0.227***	0.205***
	(5.052)	(4.372)
Population	0.833***	0.893***
	(7.401)	(7.747)
GDPG	-0.077	-0.198*
	(-0.751)	(-1.736)
OADR	-0.008**	-0.006
	(-1.993)	(-1.582)
Education	0.007	-0.008
	(0.433)	(-0.524)
CPI	-0.335	-0.228
	(-0.482)	(-0.324)
Constant	-1.159	-1.249
	(-0.354)	(-0.376)
Observations	341	310
Adj. R-squared	0.998	0.998
Province FE	Yes	Yes
Year FE	Yes	Yes

Panel B. E-commerce

Variables	*Digitalization_Coverage*	*F. Digitalization_Coverage*
	(1)	(2)
E-commerce	-0.001	-0.002
	(-0.165)	(-0.352)
Population	1.041***	1.042***
	(7.232)	(6.801)
GDPG	-0.114	-0.251*
	(-1.041)	(-1.948)
OADR	0.002	0.003
	(0.375)	(0.591)
Education	-0.002	-0.006
	(-0.113)	(-0.350)
CPI	0.222	-0.168
	(0.305)	(-0.220)
Constant	-3.462	-1.125
	(-1.012)	(-0.312)
Observations	279	248
Adj. R-squared	0.997	0.997
Province FE	Yes	Yes
Year FE	Yes	Yes

This table presents the results of the impact of infrastructure on digitalization coverage. Panel A analyzes mobile phone penetration rate, while Panel B focuses on e-commerce. In both panels, Columns (1) shows current period result, and Column (2) presents results for the *t+1* period. *t*-statistics are presented in parentheses, where *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 4.6 The influence of infrastructure on digitalization level

Panel A. E-commerce

Variables	(1)	(2)
	Digitalization_Level	*F. Digitalization_Level*
E-commerce	0.082***	0.097***
	(5.960)	(5.362)
Population	1.355**	2.062***
	(2.457)	(3.418)
GDPG	-0.764*	-0.213
	(-1.825)	(-0.419)
OADR	0.044**	0.067***
	(2.527)	(3.544)
Education	-0.129**	-0.028
	(-2.006)	(-0.402)
CPI	1.582	2.791
	(0.569)	(0.929)
Constant	-8.905	-17.977
	(-0.680)	(-1.266)
Observations	279	248
Adj. R-squared	0.931	0.900
Province FE	Yes	Yes
Year FE	Yes	Yes

Panel B. Mobile Phone

Variables	(1)	(2)
	Digitalization_Level	*F. Digitalization_Level*
Mobile Phone	-0.213	-0.157
	(-1.211)	(-0.843)
Population	1.607***	1.643***
	(3.654)	(3.583)
GDPG	-0.630	-0.313
	(-1.563)	(-0.690)
OADR	0.085***	0.100***
	(5.659)	(6.389)
Education	-0.058	0.073
	(-0.933)	(1.153)
CPI	4.378	3.045
	(1.609)	(1.089)
	-25.484**	-19.921
Constant	(-1.990)	(-1.509)
Observations	341	310
Adj. R-squared	0.976	0.961
Province FE	Yes	Yes
Year FE	Yes	Yes

This table presents the results of the impact of e-commerce on digitalization level. Panel A focuses on e-commerce, while Panel B analyzes mobile phones. In both panels, Columns (1) shows current period results, and Column (2) presents the results for the *t+1* period. *t*-statistics are presented in parentheses, where *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

6. Conclusion and policy implication

6.1 Conclusion

This chapter focuses on the development and implementation of e-CNY from the aspects of money supply, money demand, and financial infrastructure. By investigating the influence of the widespread adoption of digital payments on physical currency, it infers the future dynamics of e-CNY's supply and demand. Through the analysis of provincial-level panel data, we find a negative correlation between the extensive of digitalization development and the demand and supply for physical currency, indicating that the continuous development of digital payment systems could have far-reaching implications for the future promotion and application of e-CNY.

To begin with, this study we find that digitization, measured by digitalization coverage and level, significantly reduces individuals and businesses' reliance on physical cash, indicating a strong shift toward e-CNY. The rapid expansion of mobile payments, such as Alipay and WeChat Payment, and e-commerce has reshaped China's monetary landscape, facilitating a transition from cash-based transactions to digital alternatives. This trend creates a favorable environment for the promotion of e-CNY. As the two dimensions of "digitalization of physical wallet" and "digitalization of payment scenario" show that the diversification of digital payment scenarios and the gradual transition to digital wallets are paving the way for the widespread adoption of e-CNY.

In addition, we find that demographic factors also play a role in this transition. Provinces with larger population support e-CNY adoption by lowering per capita infrastructure costs, while provinces with aging population remains more dependent on physical cash. This is primarily because a large population can significantly reduce the per capita cost of establishing e-CNY infrastructure, and effectively lower the cost of transactions. However, it has been observed that an aging demographic increases both the supply and demand for physical currency. This implies that an aging population could present challenges to the rapid adoption and implementation of digital currencies, as older individuals may be slower to adapt to digital innovations, including digital currencies. Interestingly, education levels have little impact, suggesting that the digital payment ecosystem in China has become intuitive and widely accepted, and the educational barriers to e-CNY adoption are minimal. This is partly due to the Chinese government's commitment to education development since 1986, which has significantly improved the overall education level among Chinese residents.

To conclude, by employing an indirect observation method, this research reveals the relationship between the development of digitalization and physical currency, providing a new perspective for exploring the future development of e-CNY. Unlike previous CBDC studies, which primarily focused on theoretical frameworks, this study contributes empirical evidence to support the development of CBDCs. Specifically, our research confirms a significant relationship between the rise of digital payment systems and the decline in the use of physical cash, further suggesting that e-CNY has the potential to gradually replace cash in the future. Although the study focuses on China, the trend of digital payment adoption is prevalent worldwide. For countries with relatively advanced electronic payment infrastructures, such as Sweden and South Korea, the Chinese experience may offer valuable insights to gradually promote their CBDC initiatives. And for countries with less developed digital payment infrastructures, it may serve as a possible reference framework on the necessary foundations for future CBDC implementation.

According to the above findings, we further conclude the following statements.

First, the digitalization of physical wallet acts as a prerequisite to the digitalization of currency. At the heart of this transformation are widespread adoptions of smartphones, which serves as the portable and intelligent carriers for digital wallets, has bridged the "last mile" and would provide individuals a ubiquitous platform to store, manage, and transact with e-CNY.

Second, the expansion of digital payment scenarios, particularly through the growth of e-commerce, strengthens the foundation for e-CNY’s implementation. By enriching the digital payment ecosystems, this shift fosters new digital payment habits and reduces reliance on physical currency.

Furthermore, the supply and demand for e-CNY may be relatively higher in areas where digitalization is underdeveloped and there is significant reliance on physical currency. The introduction of CBDCs in these regions could potentially stimulate demand for digital financial services and fulfill unmet digital payment needs. While the transition from traditional paper currency to electronic payments tends to progress gradually in technologically advanced regions, in less developed areas, the shift towards digital currencies may occur more rapidly, potentially bypassing intermediate stages of payment evolution, depending on the readiness of local infrastructure.

Therefore, we foresee digitalization of CNY as both conditional and inevitable, although overcoming developmental challenges will take time. While the technology is already at a stage where implementation is feasible[1], the necessary infrastructure, regulation, and the corresponding legal framework for e-CNY still require further

[1] As of January 2024, the domestic transaction volume of e-CNY within China has reached 2 trillion Chinese RMB, and the UAE has successfully conducted a cross-border transfer of 50 million AED to the People's Bank of China using the mBridge platform for digital currency transactions.

development and refinement. We infer that with the gradual implementation of e-CNY, China's monetary system will undergo a transformation within the next 10 to 20 years. However, this transformation will face several obstacles, including the need for robust technical infrastructure and the creation of an effective regulatory framework. In light of these challenges, policymakers should prioritize ensuring technological security, safeguarding user privacy, and maintaining the stability of the payment system as digital currencies are promoted.

6.2 Policy implication

We propose a few policy implications and recommendations as follows:

The transition to a fully digitized fiat currency system requires comprehensive reforms across various aspects of legal and regulatory frameworks. The complete replacement of physical banknotes with digital currency may inadvertently infringe upon the public's right to use physical legal tender. This shift may disproportionately affect individuals who are less familiar with digital technology or those residing in regions with insufficient digital infrastructure, exacerbating digital inequality. Therefore, policymakers must carefully design and implement legal reforms that promote financial inclusivity and ensure no one is excluded from the economy due to technological disadvantages. Additionally, to build public trust in innovative digital money, it is essential for policymakers and financial institutions to prioritize privacy protection and security in the use of e-CNY. Particular attention should be given to vulnerabilities in digital wallet designs, especially in the event of mobile device loss.

In addition, commercial banks need to transform to adapt to the introduction of CBDC. As digital currencies become more prevalent, banks need to shift away from their conventional business models, which have largely depended on physical branches and customer acquisition through extensive networks, and move towards a more technology-driven approach. The future competitiveness of banks will hinge on their ability to embrace technological innovation, such as upgrading technology, offering precise and intelligent services, and creating diversified digital application scenarios.

CHAPTER FIVE CONCLUSION

1. Summary of main results

1.1 Essay one

Chapter two provides a comprehensive literature survey on digital currency. Initially, Bitcoin and other cryptocurrencies led the digital currency wave as representatives of private digital currencies. However, the literature indicates that the future viability of these private digital currencies is increasingly constrained by regulatory challenges, market volatility, and their limitations as stable stores of value and mediums of exchange. In contrast, this survey concludes that CBDC is poised to be the future of digital currency. As CBDCs emerge as a dominant trend, they demonstrate increasingly broad application prospects and the potential to shape the future of financial systems worldwide.

1.2 Essay two

By utilizing a large sample of the top 50 countries over the period from 2005 to 2022, chapter three find that the development of a country's CBDC significantly strengthens the transmission of exchange rate changes into changes in the prices of traded commodities, suggesting an enhanced invoicing power of the country's currency. We also find this effect is even stronger in CBDC pilot countries. Mechanism tests reveal that the development signal of CBDC enhances the currency invoicing power by decreasing exchange rate volatility and increasing currency liquidity in international foreign exchange market. These effects make it a more attractive choice for international invoicing.

1.3 Essay three

In Chapter four, we choose China as a specific case for analyzing CBDC's conditions and implementations. By providing empirical insights into the exploration of CBDCs with the case of e-CNY within the context of China's digital economy ecosystem, we find the digitalization development reduces both the supply and demand of paper currency substantially, indirectly suggesting that the digitalization has paved the way for the promotion of e-CNY which aims to replace physical currency in the near future. Our further analysis examines the impact of the digital infrastructure related to mobile phone and the e-commerce degree based on the mobile payment ecosystem. The findings show that the digitalization of wallets and payment scenarios has laid a solid foundation for implementing e-CNY.

2. Limitation and future work

2.1 Limitations

Despite the contributions of this study, there are several limitations that should be acknowledged.

First of all, the field of financial economics predominantly relies on historical data and empirical analysis. However, digital currency, particularly central bank digital currency, represents a nascent development with very limited historical precedent and public data. The scarcity of data and practical examples poses significant challenges to this study. As a result, this research primarily offers a preliminary exploration and focuses on specific issues pertinent to the current stage of digital currency development.

In addition, although this study leverages China's experience as a microcosm to analyze broader global implications, it remains challenging to encapsulate the diverse conditions worldwide. Notably, this study does not explore the practical experiences of CBDCs in those other developed countries with advanced electronic payment systems. Cases of the European Union and the United States merit further investigation to enhance the generalizability of the findings.

2.2 Future research areas

First, CBDC is expected to play a fundamental role as the unit of account and settlement currency in future digital economies. As public data on CBDCs becomes more accessible, future research can conduct more comprehensive empirical analyses to examine their implementation across diverse national contexts. In particular, exploring how CBDC adoption differs between regions with well-developed electronic payment infrastructures and those transitioning directly from paper money to digital currency can offer valuable insights into various developmental pathways. This presents an intriguing research direction for comparing geographic regions with different levels of financial integration.

Second, based on the findings in Chapter three, the development of CBDCs could have far-reaching implications for global currency diversity. Given that the U.S. dollar possesses high liquidity and deep monetary markets, it is crucial to explore how a specific country's CBDC may influence its currency's internationalization within the context of the U.S. dollar's dominant position. A particularly compelling research area is the potential effects of the development of e-CNY on the internationalization of the Chinese yuan. Moreover, the BRICS nations are actively working toward expanding international settlements using their respective digital currencies or possibly introducing a new BRICS currency specifically for trade purposes. The development of a blockchain-based settlement platform, the "BRICS Bridge," presents an important challenge to the U.S. dollar’s hegemony and warrants further academic inquiry (COINGEEK, 2024).

Third, inspired by the third essay in Chapter four of this thesis, future research could examine the operational models of CBDCs. The public patents of e-CNY reveal three distinct operational approaches that parallel Bitcoin's UTXO structure: issuing CBDC in the smallest denomination of one cent to simplify the UTXO structure, customizing CBDC denominations to align with individual transaction amounts, and generating CBDC in fixed denominations similar to traditional currency. These innovative currency management strategies are expected to reshape future payment and settlement systems, making them an important and valuable topic of further research.

BIBLIOGRAPHY

Abad, J., Barrau, G. N., & Thomas, C. (2023). CBDC and the operational framework of monetary policy. *BIS Working Paper, No. 1126*.

Adhikary, A., Diatha, K. S., Borah, S. B., & Sharma, A. (2021). How does the adoption of digital payment technologies influence unorganized retailers' performance? An investigation in an emerging market. *Journal of the Academy of Marketing Science, 49*, 882-902.

Agur, I., Ari, A., & Dell'Ariccia, G. (2022). Designing central bank digital currencies. *Journal of Monetary Economics, 125*, 62-79.

Alden, L. (2020). *3 Reasons I'm investing in Bitcoin*. https://www.lynalden.com/invest-in-bitcoin/

Ali, R., John, B., Clews, R., & Southgate, J. (2014). Innovation in payment technologies and the emergence of digital currencies. *Bank of England Quarterly Bulletin*, 262-275.

Allen, F., Gu, X., & Jagtiani, J. (2022). Fintech, cryptocurrencies, and CBDC: Financial structural transformation in China. *Journal of International Money and Finance, 124*, 102625.

Alora, A., Sahoo, P., & Sasidharan, A. (2024). Central bank digital currency adoption challenges-The case of an emerging nation. *Finance Research Letters, 59*, 104756.

Alvarez, F., Argente, D., & Van Patten, D. (2023). Are cryptocurrencies currencies? Bitcoin as legal tender in El Salvador. *Science, 382*(6677), eadd2844.

Amiti, M., Itskhoki, O., & Konings, J. (2014). Importers, exporters, and exchange rate disconnect. *American Economic Review, 104*(7), 1942-1978.

Amiti, M., Itskhoki, O., & Konings, J. (2022). Dominant currencies: How firms choose currency invoicing and why it matters. *The quarterly journal of economics, 137*(3), 1435-1493.

Andolfatto, D. (2021). Assessing the impact of central bank digital currency on private banks. *The Economic Journal, 131*(634), 525-540.

Andolfatto, D. (2024). Technological change and central banking. *Federal Reserve Bank of St. Louis Review, 106*(1), 1-9.

Antonakakis, N., Chatziantoniou, I., & Gabauer, D. (2019). Cryptocurrency market contagion: Market uncertainty, market complexity, and dynamic portfolios. *Journal of International Financial Markets, Institutions and Money, 61*, 37-51.

Aoyama, R. (2016). “One belt, one road”: China's new global strategy. *Journal of Contemporary East Asia Studies, 5*(2), 3-22.

Arslanalp, S., Eichengreen, B., & Simpson-Bell, C. (2024). Dollar dominance in the international reserve system: An update. *IMF Blog*. https://www.imf.org/en/Blogs/Articles/2024/06/11/dollar-dominance-in-the-international-reserve-system-an-update

Atlantic council. (2024). *Central bank digital currencies status*. https://cbdctracker.org/

Auer, R., Cornelli, G., & Frost, J. (2023). Rise of the central bank digital currencies. *International Journal of Central Banking, 19*(4), 185-214.

Auer, R., Frost, J., Gambacorta, L., Monnet, C., Rice, T., & Shin, H. S. (2022). Central bank digital currencies: Motives, economic implications, and the research frontier. *Annual Review of Economics, 14*(1), 697-721.

Avgouleas, E., & Blair, W. (2024). A critical evaluation of central bank digital currencies (CBDCs): payments’ final frontier? *Capital Markets Law Journal, 19*(2), 103-112.

Aysan, A. F., Demir, E., Gozgor, G., & Lau, C. K. M. (2019). Effects of the geopolitical risks on Bitcoin returns and volatility. *Research in International Business and Finance, 47*, 511-518.

Baek, C., & Elbeck, M. (2015). Bitcoins as an investment or speculative vehicle? A first look. *Applied Economics Letters, 22*(1), 30–34.

Bagnall, J., Bounie, D., Huynh, K. P., Kosse, A., Schmidt, T., Schuh, S. D., & Stix, H. (2014). Consumer cash usage: A cross-country comparison with payment diary survey data.

Bank, E. C. (2015). Virtual currency schemes - a further analysis. *ECB Working Paper*.

Bank for International Settlements. (2000). Survey of electronic money developments. *CPMI working paper, 38*.

Bank for International Settlements. (2004). Survey of development in electronic money and internet and mobile payment. *BIS Working Paper*.

Bank for International Settlements. (2018). Central bank digital currencies. *BIS Working Paper*.

Bank for International Settlements. (2020). Central bank digital currencies: Foundational principles and core features. *BIS Working Paper*.

Bank for International Settlements. (2021a). Central bank digital currencies: An opportunity for the monetary system. *BIS Working Paper, Annual Economic Report*

Bank for International Settlements. (2021b). Financial stability implications. *BIS Working Paper*.

Bank for International Settlements. (2022). Gaining momentum—Results of the 2021 BIS survey on central bank digital currencies. *BIS Working Paper*.

Bank for International Settlements, Bank of Canada, European Central Bank, Bank of Japan, Sveriges Riksbank, Swiss National Bank, Bank of England, & Board of Governors Federal Reserve System. (2020). Central bank digital currencies: Foundational principles and core features. *BIS Working Paper*.

Bank for International Settlements and the World Bank. (2022). Central bank digital currencies: A new tool in the financial inclusion toolkit? FSI Insights on Policy Implementation *BIS Working Paper, No. 41*.

Bank of Canada. (2018). *Digital currencies and fintech: projects*. https://www.bankofcanada.ca/research/digital-currencies-and-fintech/projects/

Bank of Canada, Bank of England, & Monetary Authority in Singapore. (2018). Cross-border interbank payments and settlements: emerging opportunities for digital transformation. *BIS Working Paper*.

Bank of England. (2021). Bank of England statement on central bank digital currency. *Working Paper*.

Barrdear, J., & Kumhof, M. (2022). The macroeconomics of central bank digital currencies. *Journal of Economic Dynamics and Control, 142*, 104148.

Barro, R. J., & Lee, J. W. (2013). A new data set of educational attainment in the world, 1950–2010. *Journal of development economics, 104*, 184-198.

Bartram, S. M., & Bodnar, G. M. (2007). The exchange rate exposure puzzle. *Managerial Finance, 33*(9), 642-666.

Baur, D. G., Dimpfl, T., & Kuck, K. (2018). Bitcoin, gold and the US dollar–A replication and extension. *Finance Research Letters, 25*, 103-110.

Bech, M., & Garratt, R. (2017). Central bank cryptocurrencies. *Bank of International Settlements Quarterly Review September*, 55-70.

Bech, M. L., Faruqui, U., Ougaard, F., & Picillo, C. (2018). Payments are a-changin'but cash still rules. *BIS Quarterly Review, March*.

Beigman, E., Brennan, G., Hsieh, S.-F., & Sannella, A. J. (2023). Dynamic principal market determination: Fair value measurement of cryptocurrency. *Journal of*

Accounting, Auditing & Finance, 38(4), 731-748.

Belchior, R., Vasconcelos, A., Guerreiro, S., & Correia, M. (2021). A survey on blockchain interoperability: Past, present, and future trends. *ACM Computing Surveys (CSUR), 54*(8), 1-41.

Berger, A. N., & Bouwman, C. H. (2013). How does capital affect bank performance during financial crises? *Journal Of Financial Economics, 109*(1), 146-176.

Betts, C., & Devereux, M. B. (2000). Exchange rate dynamics in a model of pricing-to-market. *Journal of International Economics, 50*(1), 215-244.

Bian, W., Ji, Y., & Wang, P. (2021). The crowding-out effect of central bank digital currencies: A simple and generalizable payment portfolio model. *Finance Research Letters, 43*, 102010.

Bindseil, U. (2020). Tiered CBDC and the financial system. *Available at SSRN 3513422*.

BIS. (2024). *BIS triennial survey*. https://www.bis.org/statistics/rpfx22_fx.htm

Boar, C., Holden, H., & Wadsworth, A. (2020). *Impending arrival–a sequel to the survey on central bank digital currency* (BIS Working Papers, Issue. B. f. I. Settlements.

Böhme, R., Christin, N., Edelman, B., & Moore, T. (2015). Bitcoin: Economics, technology, and governance. *Journal of Economic Perspectives, 29*(2), 213-238.

Bolt, W., & Van Oordt, M. R. (2020). On the value of virtual currencies. *Journal of Money, Credit and Banking, 52*(4), 835-862.

Bouri, E., Gupta, R., & Roubaud, D. (2019). Herding behaviour in cryptocurrencies. *Finance Research Letters, 29*, 216-221.

Boz, E., Casas, C., Georgiadis, G., Gopinath, G., Le Mezo, H., Mehl, A., & Nguyen, T. (2022). Patterns of Invoicing currency in global trade: New evidence. *Journal of International Economics, 136*, 103604.

Boz, E., Gopinath, G., & Plagborg-Møller, M. (2017). Global trade and the dollar. *National Bureau of Economic Research, No. w23988*.

Brauneis, A., & Mestel, R. (2018). Price discovery of cryptocurrencies: Bitcoin and beyond. *Economics Letters, 165*, 58-61.

Brenner, M., Pasquariello, P., & Subrahmanyam, M. (2009). On the volatility and comovement of US financial markets around macroeconomic news announcements. *Journal of Financial and Quantitative Analysis, 44*(6), 1265-1289.

Briere, M., Oosterlinck, K., & Szafarz, A. (2015). Virtual currency, tangible return: Portfolio diversification with bitcoin. *Journal Of Asset Management, 16*(6), 365-373.

Brown, M., Hentschel, N., Mettler, H., & Stix, H. (2022). The convenience of electronic payments and consumer cash demand. *Journal of Monetary Economics, 130*, 86-102.

Brunnermeier, M. K., & Niepelt, D. (2019). On the equivalence of private and public money. *Journal of Monetary Economics, 106*, 27-41.

Buckley, R. P., & Trzecinski, M. (2023). Central bank digital currencies and the global financial system: the dollar dethroned? *Capital Markets Law Journal, 18*(2), 137-171.

Buterin, V. (2016). Chain interoperability. *R3 Research Paper*.

Calvo, M. G., & Gramont, M. C. A. V. (1992). Currency substitution in developing countries: an introduction. *IMF working paper*.

Carapella, F., & Flemming, J. (2020). Central bank digital currency: A literature review.

Cassel, G. (1918). Abnormal deviations in international exchanges. *The Economic Journal, 28*(112), 413-415.

Chaim, P., & Laurini, M. P. (2018). Volatility and return jumps in bitcoin. *Economics Letters, 173*, 158-163.

Chaum, D. (1983). Blind signatures for untraceable payments. Advances in Cryptology: Proceedings of Crypto 82,

Chaum, D. L. (1979). *Computer systems established, maintained, and trusted by mutually suspicious groups*. Electronics Research Laboratory, University of California.

Cheikh, N. B., Zaied, Y. B., & Ameur, H. B. (2023). Recent developments in exchange rate pass-through: What have we learned from uncertain times? *Journal of International Money and Finance, 131*, 102805.

Chen, H., & Siklos, P. L. (2022). Central bank digital currency: A review and some macro-financial implications. *Journal Of Financial Stability, 60*, 100985.

Chen, H., & Siklos, P. L. (2023). Currency substitution in a world of looming retail CBDCs: Suggestive currency substitution-based evidence. *Journal of International Financial Markets, Institutions and Money, 88*, 101828.

Chen, J., Leung, W. S., & Goergen, M. (2017). The impact of board gender composition on dividend payouts. *Journal of Corporate Finance, 43*, 86-105.

Cheung, A., Roca, E., & Su, J.-J. (2015). Crypto-currency bubbles: An application of the Phillips–Shi–Yu (2013) methodology on Mt. Gox bitcoin prices. *Applied Economics, 47*(23), 2348-2358.

Ching, A. T., & Hayashi, F. (2010). Payment card rewards programs and consumer payment choice. *Journal of Banking & Finance, 34*(8), 1773-1787.

Chiu, J., Davoodalhosseini, M., Jiang, J., & Zhu, Y. (2019). Central bank digital currency and banking (No. 2019-20). *Bank of Canada Staff Working Paper*.

Chiu, J., & Davoodalhosseini, S. M. (2023). Central bank digital currency and banking: Macroeconomic benefits of a cash-like design. *Management Science, 69*(11), 6708-6730.

Chiu, J., Davoodalhosseini, S. M., Jiang, J., & Zhu, Y. (2023). Bank market power and central bank digital currency: Theory and quantitative assessment. *Journal of Political Economy, 131*(5), 1213-1248.

Chokor, A., & Alfieri, E. (2021). Long and short-term impacts of regulation in the cryptocurrency market. *The Quarterly Review of Economics and Finance, 81*, 157-173.

Christian, B., & Henry, H. (2019). Proceeding with Caution - A Survey on Central Bank Digital Currency (January 8, 2019). *BIS Working Papers*(101).

Ciaian, P., Rajcaniova, M., & Kancs, d. A. (2016). The economics of Bitcoin price formation. *Applied Economics, 48*(19), 1799-1815.

Claessens, S., Cong, L. W., Moshirian, F., & Park, C.-Y. (2024). Opportunities and challenges associated with the development of FinTech and Central Bank Digital Currency. *Journal Of Financial Stability*, 101280.

Cochrane, J. H. (2017). The new-Keynesian liquidity trap. *Journal of Monetary Economics, 92*, 47-63.

Cohen, B. J. (2001). Electronic money: New day or false dawn? *Review of International Political Economy, 8*(2), 197-225.

COINGEEK. (2024). *BRICS countries consider blockchain-based stablecoin settlements*. https://coingeek.com/brics-countries-consider-blockchain-based-stablecoin-settlements/

Committee on Payments and Market Infrastructures. (2015). Digital currencies. *BIS Working Paper, November*.

Committee on Payments and Market Infrastructures. (2018). Central bank digital currencies. *BIS Working Paper, March*.

Conti, M., Kumar, E. S., Lal, C., & Ruj, S. (2018). A survey on security and privacy issues of bitcoin. *IEEE Communications Surveys & Tutorials, 20*(4), 3416-3452.

Coppola, A., Krishnamurthy, A., & Xu, C. (2023). *Liquidity, debt denomination, and currency dominance*.

Corbet, S., Larkin, C., Lucey, B. M., Meegan, A., & Yarovaya, L. (2020). The impact of macroeconomic news on Bitcoin returns. *The European Journal of Finance, 26*(14), 1396-1416.

Corbet, S., Meegan, A., Larkin, C., Lucey, B., & Yarovaya, L. (2018). Exploring the dynamic relationships between cryptocurrencies and other financial assets. *Economics Letters, 165*, 28-34.

Dahlberg, T., Guo, J., & Ondrus, J. (2015). A critical review of mobile payment research. *Electronic Commerce Research and Applications, 14*(5), 265-284.

Dai, W. (1998). B-money proposal. *White paper*.

Danezis, G., & Meiklejohn, S. (2015). Centrally banked cryptocurrencies. *arXiv preprint arXiv:1505.06895*.

Das, M. M., Griffoli, M. T. M., Nakamura, F., Otten, M. J., Soderberg, G., Sole, M. J., & Tan, B. (2023). *Implications of central bank digital currencies for monetary policy transmission*. International Monetary Fund.

David, B., Abel, F., & Patrick, W. (2016). Debit card and demand for cash. *Journal of Banking & Finance, 73*, 55-66.

Davoodalhosseini, S. M. (2022). Central bank digital currency and monetary policy. *Journal of Economic Dynamics and Control, 142*, 104150.

De Blasis, R., Galati, L., Webb, A., & Webb, R. I. (2023). Intelligent design: stablecoins (in) stability and collateral during market turbulence. *Financial Innovation, 9*(1), 85.

Demirguc-Kunt, A., Klapper, L., Singer, D., & Ansar, S. (2018). *The global findex database 2017: Measuring financial inclusion and the fintech revolution*.

Denmark National Bank. (2017). *Central bank digital currency in Denmark?*

Devereux, M. B., Engel, C., & Storgaard, P. E. (2004). Endogenous exchange rate pass-through when nominal prices are set in advance. *Journal of International Economics, 63*(2), 263-291.

Di Iorio, A., Kosse, A., & Mattei, I. (2024). Embracing diversity, advancing together-results of the 2023 BIS survey on central bank digital currencies and crypto. *BIS*

Working Paper, 147.

Dodgson, M., Gann, D., Wladawsky-Berger, I., Sultan, N., & George, G. (2015). Managing digital money. *Academy of management journal, 58*(2), 325-333.

Dyhrberg, A. H. (2016). Bitcoin, gold and the dollar–A GARCH volatility analysis. *Finance Research Letters, 16*, 85-92.

Dyhrberg, A. H., Foley, S., & Svec, J. (2018). How investible is Bitcoin? Analyzing the liquidity and transaction costs of Bitcoin markets. *Economics Letters, 171*, 140–143.

Engel, C. (1993). Real exchange rates and relative prices: An empirical investigation. *Journal of Monetary Economics, 32*(1), 35-50.

European Commission. (2017). *European interoperability framework*.

Fama, E. (1965). The behavior of stock-market prices. *The journal of Business, 38*(1), 34–105.

Favarel-Garrigues, G., Godefroy, T., & Lascoumes, P. (2011). Reluctant partners? Banks in the fight against money laundering and terrorism financing in France. *Security Dialogue, 42*(2), 179-196.

Feng, W., Wang, Y., & Zhang, Z. (2018a). Can cryptocurrencies be a safe haven: A tail risk perspective analysis. *Applied Economics, 50*(44), 4745-4762.

Feng, W., Wang, Y., & Zhang, Z. (2018b). Informed trading in the Bitcoin market. *Finance Research Letters, 26*, 63-70.

Fernández-Villaverde, J., Sanches, D., Schilling, L., & Uhlig, H. (2021). Central bank digital currency: Central banking for all? *Review of Economic Dynamics, 41*, 225-242.

Fisher, I. (1930). *The theory of interest*.

Fisher, I. (2006). *The purchasing power of money: Its' determination and relation to credit interest and crises*. Cosimo, Inc.

Foley, S., Karlsen, J. R., & Putniņš, T. J. (2019). Sex, drugs, and bitcoin: How much illegal activity is financed through cryptocurrencies? *The Review of Financial Studies, 32*(5), 1798-1853.

Fry, J. (2018). Booms, busts and heavy-tails: The story of Bitcoin and cryptocurrency markets? *Economics Letters, 171*, 225-229.

Fry, J., & Cheah, E.-T. (2016). Negative bubbles and shocks in cryptocurrency markets. *International Review of Financial Analysis, 47*, 343-352.

Gaies, B., Nakhli, M. S., Sahut, J. M., & Guesmi, K. (2021). Is Bitcoin rooted in confidence?–Unraveling the determinants of globalized digital currencies. *Technological Forecasting and Social Change, 172*, 121038.

Garzik, J., & Donnelly, J. C. (2018). Blockchain 101: an introduction to the future. In *Handbook of Blockchain, Digital Finance, and Inclusion, Volume 2* (pp. 179-186). Elsevier.

Georgieva, K. (2022). The future of money: Gearing up for central bank digital currency. *IMF working paper*.

Gerding, F., & Hartley, J. S. (2024). De-dollarization? Not so fast. *Economics Letters, 238*, 111665.

Ghasseminejad, S., & Jahan-Parvar, M. R. (2021). The impact of financial sanctions: The case of Iran. *Journal of Policy Modeling, 43*(3), 601-621.

Girton, L., & Roper, D. (1981). Theory and implications of currency substitution. *Journal of Money, Credit and Banking, 13*(1), 12-30.

Giudici, G., Milne, A., & Vinogradov, D. (2020). Cryptocurrencies: market analysis and perspectives. *Journal of Industrial and Business Economics, 47*, 1-18.

Giudici, P., & Abu-Hashish, I. (2019). What determines bitcoin exchange prices? A network VAR approach. *Finance Research Letters, 28*, 309-318.

Gkillas, K., & Katsiampa, P. (2018). An application of extreme value theory to cryptocurrencies. *Economics Letters, 164*, 109-111.

Glaser, F., Zimmermann, K., Haferkorn, M., Weber, M. C., & Siering, M. (2014). Bitcoin-asset or currency? Revealing users' hidden intentions. *Twenty Second European Conference on Information Systems (April 15, 2014). ECIS, ECIS*.

Goldberg, L. S., & Tille, C. (2008). Vehicle currency use in international trade. *Journal of International Economics, 76*(2), 177-192.

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Gopinath, G., Boz, E., Casas, C., Díez, F. J., Gourinchas, P.-O., & Plagborg-Møller, M. (2020). Dominant currency paradigm. *American Economic Review, 110*(3), 677-719.

Gopinath, G., & Stein, J. C. (2021). Banking, trade, and the making of a dominant currency. *The quarterly journal of economics, 136*(2), 783-830.

Griffin, J. M., & Shams, A. (2019). Is Bitcoin really untethered? *The Journal of Finance, 75(4)*, 1913–1964.

Grinberg, R. (2012). Bitcoin: An innovative alternative digital currency. *Hastings Science & Technology Law Journal, 4*, 160.

Guesmi, K., Saadi, S., Abid, I., & Ftiti, Z. (2018). Portfolio diversification with virtual currency: evidence from bitcoin. *International Review of Financial Analysis, 63*, 431-437.

Guo, Z., & Dan, M. (2023). Catching the fast payments trend: Optimal designs and leadership strategies of retail payment and settlement systems. *MIS Quarterly, 47*(2), 669.

Hägele, S. (2024). Centralized exchanges vs. decentralized exchanges in cryptocurrency markets: A systematic literature review. *Electronic Markets, 34*(1), 33.

Harvey, C. R., & Rabetti, D. (2024). International business and decentralized finance. *Journal of International Business Studies*, 1-24.

Hayek, F. A. (1978). *Denationalisation of money—The argument refined: An analysis of the theory and practice of concurrent currencies* (2nd ed.). London: Institute of Economic Affairs.

Hayes, A. S. (2017). Cryptocurrency value formation: An empirical study leading to a cost of production model for valuing bitcoin. *Telematics And Informatics, 34*, 1308-1321.

Haykir, O., & Yagli, I. (2022). Speculative bubbles and herding in cryptocurrencies. *Financial Innovation, 8*(1), 78.

Hoang, L. T., & Baur, D. G. (2020). How stable are stablecoins? *The European Journal of Finance*, 1-17.

Hoang, Y. H., Ngo, V. M., & Vu, N. B. (2023). Central bank digital currency: A systematic literature review using text mining approach. *Research in International Business and Finance, 64*, 101889.

Hong Kong Financial Development Council. (2021). Recent development of central bank's digital currency.

Howell, S. T., Niessner, M., & Yermack, D. (2020). Initial coin offerings: Financing growth with cryptocurrency token sales. *The Review of Financial Studies, 33*(9), 3925-3974.

Huang, Y., Wang, X., & Wang, X. (2020). Mobile payment in China: Practice and its effects. *Asian Economic Papers, 19*(3), 1-18.

Hui, C.-H., Lo, C.-F., Chau, P.-H., & Wong, A. (2020). Does Bitcoin behave as a currency? A standard monetary model approach. *International Review of Financial Analysis, 70*, 101518.

Hull, I., & Sattath, O. (2024). The properties of contemporary money. *Journal of Economic Surveys, 38*(4), 1132-1155.

Humbani, M., & Wiese, M. (2019). An integrated framework for the adoption and continuance intention to use mobile payment apps. *International Journal of Bank Marketing, 37*(2), 646-664.

International Monetary Fund. (2023). Central bank digital currency—Initial considerations. *IMF working paper, 2023/060*.

Iwańczuk-Kaliska, A. (2024). Potential implications of retail central bank digital currency for banking systems identified in the literature and by central banks. *Accounting, Economics, and Law: A Convivium, 14*(2), 271-303.

Jaramillo, L., & Weber, A. (2013). *Global spillovers into domestic bond markets in emerging market economies*. International Monetary Fund.

Ji, Q., Bouri, E., Lau, C. K. M., & Roubaud, D. (2019). Dynamic connectedness and integration in cryptocurrency markets. *International Review of Financial Analysis, 63*, 257-272.

Jiang, Y., Nie, H., & Ruan, W. (2017). Time-varying long-term memory in bitcoin market. *Finance Research Letters, 25*, 280-284.

John, B., & Kumhof, M. (2016). The Macroeconomics of Central Bank Issued Digital Currencies. *Staff Working Paper. Bank of England.*

Jun, J., & Yeo, E. (2021). Central bank digital currency, loan supply, and bank failure risk: a microeconomic approach. *Financial Innovation, 7*(1), 81.

Karame, G. O., Androulaki, E., & Capkun, S. (2012). Double-spending fast payments in bitcoin. Proceedings of the 2012 ACM conference on Computer and communications security,

Katsiampa, P. (2017). Volatility estimation for Bitcoin: A comparison of GARCH models. *Economics Letters, 158*, 3-6.

Katsiampa, P., Corbet, S., & Lucey, B. (2019). Volatility spillover effects in leading cryptocurrencies: A BEKK-MGARCH analysis. *Finance Research Letters, 29*, 68–74.

Keynes, J. M. (1936). *The general theory of employment, interest and money*. London: Macmillan.

Keynes, J. M. (1937). The general theory of employment. *The quarterly journal of* *economics, 51*(2), 209-223.

Khan, D., Jung, L. T., & Hashmani, M. A. (2021). Systematic literature review of challenges in blockchain scalability. *Applied Sciences, 11*(20), 9372.

Khiaonarong, M. T., & Humphrey, D. (2022). *Falling use of cash and demand for retail central bank digital currency*. International Monetary Fund.

Kiff, M. J., Alwazir, J., Davidovic, S., Farias, A., Khan, M. A., Khiaonarong, M. T., Malaika, M., Monroe, M. H. K., Sugimoto, N., & Tourpe, H. (2020). A survey of research on retail central bank digital currency.

Kim, Y. S., & Kwon, O. (2023). Central bank digital currency, credit supply, and financial stability. *Journal of Money, Credit and Banking, 55*(1), 297-321.

Kosse, A., & Mattei, I. (2022). Gaining momentum–Results of the 2021 BIS survey on central bank digital currencies. *BIS Working Paper*.

Kosse, A., & Mattei, I. (2023). Making headway-Results of the 2022 BIS survey on central bank digital currencies and crypto. *BIS Working Paper*.

Koutmos, D. (2018b). Liquidity uncertainty and Bitcoin's market microstructure. *Economics Letters, 172*, 97– 101.

Krugman, P. (1980). Scale economies, product differentiation, and the pattern of trade. *American Economic Review, 70*(5), 950-959.

Kshetri, N. (2021). Blockchain and sustainable supply chain management in developing countries. *International Journal of Information Management, 60*, 102376.

Kumhof, M., & Noone, C. (2021). Central bank digital currencies—Design principles for financial stability. *Economic Analysis and Policy,*
Bank of England Working Paper, 71, 553-572.

Lamothe-Fernández, P., Alaminos, D., Lamothe-López, P., & Fernández-Gámez, M. A. (2020). Deep learning methods for modeling bitcoin price. *Mathematics, 8*(8), 1245.

Lee, A., Malone, B., & Wong, P. (2020). Tokens and accounts in the context of digital currencies.

Leonardos, S., Reijsbergen, D., & Piliouras, G. (2020). Presto: A systematic framework for blockchain consensus protocols. *IEEE Transactions on Engineering Management, 67*(4), 1028-1044.

Li, J., & Kassem, M. (2021). Applications of distributed ledger technology (DLT) and Blockchain-enabled smart contracts in construction. *Automation in construction, 132*, 103955.

Li, J., Li, N., Peng, J., Cui, H., & Wu, Z. (2019). Energy consumption of cryptocurrency mining: A study of electricity consumption in mining cryptocurrencies. *Energy, 168*, 160-168.

Liu, M., Li, G., Li, J., Zhu, X., & Yao, Y. (2021). Forecasting the price of Bitcoin using deep learning. *Finance Research Letters, 40*, 101755.

Liu, M., Li, R. Y. M., & Deeprasert, J. (2024). Factors that affect individuals in using digital currency electronic payment In China: SEM and fsQCA approaches. *International Review of Economics & Finance, 95*, 103418.

Liu, W., Liang, X., & Cui, G. (2020). Common risk factors in the returns on cryptocurrencies. *Economic Modelling, 86*, 299-305.

Liu, Y., & Tsyvinski, A. (2021). Risks and returns of cryptocurrency. *The Review of Financial Studies, 34*(6), 2689-2727.

Liu, Z. Z., & Papa, M. (2022). *Can BRICS de-dollarize the global financial system?* Cambridge University Press.

Lukonga, I. (2023). Monetary policy implications of central bank digital currencies. *IMF working paper, 2023/060*.

Lyons, R. K., & Viswanath-Natraj, G. (2023). What keeps stablecoins stable? *Journal of International Money and Finance, 131*, 102777.

Makarov, I., & Schoar, A. (2020). Trading and arbitrage in cryptocurrency markets. *Journal Of Financial Economics, 135*(2), 293-319.

Makarov, I., & Schoar, A. (2022). Cryptocurrencies and decentralized finance (DeFi). *Brookings Papers on Economic Activity, 2022*(1), 141-215.

Mallat, N. (2007). Exploring consumer adoption of mobile payments–A qualitative study. *The Journal of Strategic Information Systems, 16*(4), 413-432.

Mancini-Griffoli, T., Peria, M. S. M., Agur, I., Ari, A., Kiff, J., Popescu, A., & Rochon, C. (2018). Casting light on central bank digital currency. *IMF staff discussion note, 8*(18), 1-39.

Mariana, C. D., Ekaputra, I. A., & Husodo, Z. A. (2021). Are Bitcoin and Ethereum safe-havens for stocks during the COVID-19 pandemic? *Finance Research Letters, 38*, 101798.

Markowitz, H. (1952). The utility of wealth. *Journal of Political Economy, 60*(2), 151-158.

Marple, T. (2021). Bigger than Bitcoin: A theoretical typology and research agenda for digital currencies. *Business and Politics, 23*(4), 439-455.

McCarthy, J. (2007). Pass-through of exchange rates and import prices to domestic inflation in some industrialized economies. *Eastern Economic Journal, 33*(4), 511-537.

McKinnon, R. I. (1988). Monetary and exchange rate policies for international financial stability: a proposal. *Journal of Economic Perspectives, 2*(1), 83-103.

Mensi, W., Rehman, M. U., Shafiullah, M., Al-Yahyaee, K. H., & Sensoy, A. (2021). High frequency multiscale relationships among major cryptocurrencies: portfolio management implications. *Financial Innovation, 7*, 1-21.

Mises, L. (2007). *The historical setting of the Austrian school of economics*. Ludwig von Mises Institute.

Mishra, B., & Prasad, E. (2024). A simple model of a central bank digital currency. *Journal Of Financial Stability*, 101282.

Mohan, V. (2022). Automated market makers and decentralized exchanges: a DeFi primer. *Financial Innovation, 8*(1), 20.

Molla, A., & Licker, P. S. (2005). eCommerce adoption in developing countries: A model and instrument. *Information & management, 42*(6), 877-899.

Monetary Authority of Singapore. (2017). Project Ubin phase 2. *Working Paper*.

Mu, C. (2020). Complying with the technological evolution and economic development trend: actively promote the legal digital currency dominated by China. *Journal of Qizhi, 11*, 65-66.

Mu, C. (2022). Balancing privacy and security: Theory and practice of the E-CNY's managed anonymity. *People's Bank of China*.

Mundell, R. A. (1961). A theory of optimum currency areas. *American Economic Review, 51(4)*, 657-665.

Nadarajah, S., & Chu, J. (2017). On the inefficiency of bitcoin. *Economics Letters, 150*, 6–9.

Nakamoto, S. (2008). Bitcoin: A Peer to Peer Electronic Cash System. Available at: https://bitcoin.org/bitcoin.pdf

Norges Bank. (2018). Central bank digital currencies. *Norges Bank Papers. No.1*.

Norges Bank. (2019). Central bank digital currencies. *Norges Bank Papers, No.2*.

Obstfeld, M., & Rogoff, K. (2000). New directions for stochastic open economy models.

Journal of International Economics, 50(1), 117-153.

Peng, S., Prentice, C., Shams, S., & Sarker, T. (2023). A systematic literature review on the determinants of cryptocurrency pricing. *China Accounting and Finance Review*(ahead-of-print).

Pennings, S., Ramayandi, A., & Tang, H. C. (2015). The impact of monetary policy on financial markets in small open economies: more or less effective during the global financial crisis? *Journal of Macroeconomics, 44*, 60–70.

People's Bank of China. (2020). *Financial Stability Report*. http://www.pbc.gov.cn/en/3688110/3688172/4000889/4000894/index.html

People's Bank of China. (2021). *Progress of research & development of e-CNY in China*. http://www.pbc.gov.cn/en/3688110/3688172/4242191/index.html

People's Bank of China. (2023). *Renminbi internationalization report*.

Qian, Y. (2019). Central bank digital currency: optimization of the currency system and its issuance design. *China Economic Journal, 12*(1), 1-15.

Qin, R. (2017). The impact of money supply and electronic money: Empirical evidence from central bank in China.

Raskin, M., & Yermack, D. (2018). Digital currencies, decentralized ledgers and the future of central banking. In *Research handbook on central banking* (pp. 474-486). Edward Elgar Publishing.

Reuters. (2024). *US 'exorbitant privilege' is alive and well*. https://www.reuters.com/markets/us/us-exorbitant-privilege-is-alive-well-2024-08-29/#:~:text=But%20America%27s%20%27exorbitant%20privilege%27%20%E2%80%93,amounts%20at%20relatively%20low%20cost

Reuters. (2025). Trump's digital dollar ban gives China and Europe's CBDCs free rein. https://www.reuters.com/markets/currencies/trumps-digital-dollar-ban-gives-china-europes-cbdcs-free-rein-2025-01-28/

Rogoff, K. (2016). *The curse of cash: How large-denomination bills aid crime and tax evasion and constrain monetary policy* (1st ed.). Princeton University Press.

Schilling, L., Fernández-Villaverde, J., & Uhlig, H. (2024). Central bank digital currency: When price and bank stability collide. *Journal of Monetary Economics*, 103554.

Selgin, G. (2015). Synthetic commodity money. *Journal Of Financial Stability, 17*, 92-99.

Sen. Brown, S. (2020). *Banking for All Act. S.3571 - 116th Congress (2019-2020)*.

Shahzad, M. F., Xu, S., Lim, W. M., Hasnain, M. F., & Nusrat, S. (2024). Cryptocurrency awareness, acceptance, and adoption: the role of trust as a cornerstone. *Humanities and Social Sciences Communications, 11*(1), 1-14.

Shestak, V., Kiseleva, A., & Kolesnikov, Y. (2021). Taxation issues for digital financial assets. *Social Science Computer Review*, 08944393211003919.

Smith, C. W., & Stulz, R. M. (1985). The determinants of firms' hedging policies. *Journal of Financial and Quantitative Analysis, 20*(4), 391-405.

Sovbetov, Y. (2018). Factors influencing cryptocurrency prices evidence from Bitcoin, Ethereum, Dash, Litcoin, and Monero. *Journal of Economics and Financial Analysis, 2*(2), 1-27.

Su, C.-W., Qin, M., Tao, R., Shao, X.-F., Albu, L. L., & Umar, M. (2020). Can Bitcoin hedge the risks of geopolitical events? *Technological Forecasting and Social Change, 159*, 120182.

Sun, X., Liu, M., & Sima, Z. (2020). A novel cryptocurrency price trend forecasting model based on LightGBM. *Finance Research Letters, 32*, 101084.

Sveriges Riksbank. (2017). *The Riksbank's e-krona project: Report 1*.

Sveriges Riksbank. (2018). *The Riksbank's e-krona project: Report 2*.

Sveriges Riksbank. (2020). *The Riksbank's e-krona pilot*.

Szabo, N. (1994). Smart contracts. *Unpublished manuscript*.

Tee, H.-H., & Ong, H.-B. (2016). Cashless payment and economic growth. *Financial Innovation, 2*, 1-9.

Tercero-Lucas, D. (2023). Central bank digital currencies and financial stability in a modern monetary system. *Journal Of Financial Stability, 69*, 101188.

Tiwari, A. K., Jana, R. K., Das, D., & Roubaud, D. (2018). Informational efficiency of Bitcoin—An extension. *Economics Letters, 163*, 106-109.

Umar, M. (2025). Does CBDC launch increase tax collection? empirical evidence from China. *Finance Research Letters, 71*, 106486.

Umar, Z., & Gubareva, M. (2020). A time–frequency analysis of the impact of the Covid-19 induced panic on the volatility of currency and cryptocurrency markets. *Journal of Behavioral and Experimental Finance, 28*, 100404.

Urquhart, A. (2016). The inefficiency of Bitcoin. *Economics Letters, 148*, 80–82.

USDC Center. (2018). *USDC white paper*.

van der Linden, T., & Shirazi, T. (2023). Markets in crypto-assets regulation: Does it provide legal certainty and increase adoption of crypto-assets? *Financial Innovation, 9*(1), 22.

Vidal-Tomása, D., & Ibañez, A. (2018). Semi-strong efficiency of Bitcoin. *Finance Research Letters, 27*, 259-265.

Wang, G.-J., Ma, X.-y., & Wu, H.-y. (2020). Are stablecoins truly diversifiers, hedges, or safe havens against traditional cryptocurrencies as their name suggests? *Research in International Business and Finance, 54*, 101225.

Wang, H. (2023). How to understand China's approach to central bank digital currency? *Computer Law & Security Review, 50*, 105788.

Wang, H., & Gao, S. (2024). The future of the international financial system: The emerging CBDC network and its impact on regulation. *Regulation & Governance, 18*(1), 288-306.

Wang, Z. (2023). Money laundering and the privacy design of central bank digital currency. *Review of Economic Dynamics, 51*, 604-632.

Wei, W. C. (2018). Liquidity and market efficiency in cryptocurrencies. *Economics Letters, 168*, 21-24.

White, R., Marinakis, Y., Islam, N., & Walsh, S. (2020). Is Bitcoin a currency, a technology-based product, or something else? *Technological Forecasting and Social Change, 151*, 119877.

Wilkins, C. A. (2022). Discussion of "designing central bank digital currency" by Agur, Ari and Dell'Ariccia. *Journal of Monetary Economics, 125*, 80-84.

Wong, P., & Maniff, J. L. (2020). Comparing means of payment: What role for a central bank digital currency? *FEDS Notes*, 08-13.

Woodford, M. (1998). Doing without money: controlling inflation in a post-monetary world. *Review of Economic Dynamics, 1*.

Woodford, M. (2000). Monetary policy in a world without money. *International Finance, 3*(2), 229–260.

Wronka, C. (2023). Central bank digital currencies and their potential impact on traditional banking and monetary policy: An initial analysis. *Digital Finance, 5*(3), 613-641.

Wu, B., & Zhang, M. (2024). The impact of central bank digital currency on monetary policy effectiveness. *Economic Change and Restructuring, 57*(3), 135.

Wu, Y., Fan, H., Wang, X., & Zou, G. (2019). A regulated digital currency. *Science China Information Sciences, 62*, 1-12.

Xia, H., Gao, Y., & Zhang, J. Z. (2023). Understanding the adoption context of China's digital currency electronic payment. *Financial Innovation, 9*(1), 63.

Xu, J. (2022). Developments and implications of central bank digital currency: The case of China e‐CNY. *Asian Economic Policy Review, 17*(2), 235-250.

Yang, J., & Zhou, G. (2022). A study on the influence mechanism of CBDC on monetary policy: An analysis based on e-CNY. *Plos one, 17*(7), e0268471.

Yang, Y., Chen, N., & Chen, H. (2023). The digital platform, enterprise digital transformation, and enterprise performance of cross-border e-commerce—from the perspective of digital transformation and data elements. *Journal of Theoretical and Applied Electronic Commerce Research, 18*(2), 777-794.

Yao, Q. (2018). A systematic framework to understand central bank digital currency. *Science China Information Sciences, 61*, 1-8.

Yermack, D. (2024). Is Bitcoin a real currency? An economic appraisal. In *Handbook of digital currency* (pp. 29-40). Elsevier.

Yousaf, I., Nekhili, R., & Gubareva, M. (2022). Linkages between DeFi assets and conventional currencies: Evidence from the COVID-19 pandemic. *International Review of Financial Analysis, 81*, 102082.

Zhang, W., Wang, P., Li, X., & Shen, D. (2018). Some stylized facts of the cryptocurrency market. *Applied Economics, 50*(55), 5950-5965.

APPENDIX

Appendix A. Variable definition in Chapter three

Variable Type	Sign	Definitions
Dependent variable	$\Delta P_{ij,t}$	The changes in the log of price of goods exported from country *i* to country *j* in year *t*, invoiced in currency of country *i* and measured in currency of country *j*.
Independent variables	$\Delta E_{ij,t}$	The changes in the log of bilateral exchange rate between country *i* and country *j* in year *t*.
	$Shock_{i,t}$	A dummy variable to present whether country *i* has issued a CBDC research announcement in year *t*. It takes the value of 1 for the announcement year and all subsequent years.
Control variables	$\Delta Volume_{ij,t}$	The changes in the log of goods quantity exported from country *i* to country *j* in year *t*.
	$\Delta GDP_{i,t}$	The real GDP growth rate of country *i* in year *t*.
	$\Delta GDP_{j,t}$	The real GDP growth rate of country *j* in year *t*.
	$Inflation_{i,t}$	The inflation rate of country *i* in year *t*.
	$Inflation_{j,t}$	The inflation rate of country *j* in year *t*.
	ΔWTI_{t}	The growth of the crude oil global price of West Texas Intermediate (WTI), deflated by the global GDP deflator index.
	$LnVIX_{t}$	The natural logarithm of the Chicago Board Options Exchange Volatility Index. It is a real-time index derived from S&P 500 options prices. Known as the 'fear gauge,' it reflects market expectations of volatility over the next 30 days, typically rising during periods of uncertainty."
	$Bitcoin_{i,t}$	A dummy variable to capture the impact of the presence of Bitcoin. It takes the value of 0 before 2008 and 1 after 2008.
	α_{ij}	Country level paired fixed effects for the trade pair of country *i* exporting to country *j*.
Other variables	$Variance_{i,t}$	The variance of country *i*'s real effective exchange rate.
	$Turnover_{i,t}$	The natural logarithm of the foreign exchange turnover plus one.

Appendix B. CBDC development by countries (in the top 50 GDP ranking) over time

Panel A. Timeline of CBDC Development Announcements by Country and Region	
Announcement Year	Country and Region
2014	China
2015	United Kingdom
2016	Canada, Japan, Euro area countries of Germany, Italy, Netherlands, Belgium, Ireland, Finland, and Portugal.
2017	Brazil, Israel, Poland, Sweden.
2018	Egypt, Indonesia, Iran, Turkiye.
2019	Chile, Hong Kong, Norway, Pakistan, Russian Federation, Saudi Arabia, Singapore, South Africa, Switzerland, Thailand, United Arab Emirates.
2020	Australia, India, Kazakhstan, Korea, New Zealand, United States.
2021	Austria, France, Mexico, Nigeria, Peru, Philippines, Viet Nam.
2022	Argentina, Bangladesh, Denmark, Malaysia, Spain.
Panel B. Timeline of CBDC Pilot Projects by Country and Region	
Pilot Year	Country and Region
2019	Saudi Arabia, United Arab Emirates.
2020	China, France
2021	Nigeria (Launched CBDC in 2022)
2022	India, Singapore.

Note: In Panel A, Romania has not developed a CBDC. In Panel B, as of May 2024, there are 7 countries and regions conducting CBDC pilot programs: Saudi Arabia, United Arab Emirates, China, India, France, Singapore, Korea, Russian Federation, Turkey, Switzerland, Kazakhstan, Thailand, Hong Kong, and Nigeria. (Source: Atlantic Council CBDC Tracker)

Appendix C. Global ranking of the top 50 countries by 2022 constant GDP (Billions of USD)

Rank	Country	Constant GDP	CBDC status	Rank	Country	Constant GDP	CBDC status
1	United States	20927	Research	26	Ireland	499	Research
2	China	16325	Pilot	27	Iran	488	Proof of concept
3	Japan	4530	Research	28	Egypt	454	Research
4	Germany	3634	Research	29	Thailand	450	Pilot
5	United Kingdom	3210	Research	30	Norway	434	Research
6	India	2962	Pilot	31	United Arab Emirates	431	Pilot
7	France	2638	Pilot	32	Austria	422	Research
8	Italy	1962	Research	33	Israel	408	Research
9	Brazil	1901	Proof of concept	34	Philippines	408	Proof of concept
10	Canada	1761	Research	35	Pakistan	400	Research
11	Korea	1741	Pilot	36	Malaysia	387	Research
12	Australia	1586	Research	37	Singapore	380	Pilot
13	Russian Federation	1472	Pilot	38	South Africa	361	Research
14	Spain	1324	Research	39	Viet Nam	359	Research
15	Mexico	1285	Research	40	Denmark	356	Research
16	Turkiye	1194	Pilot	41	Colombia	355	Research
17	Indonesia	1122	Research	42	Hong Kong, China	319	Pilot
18	Netherlands	895	Research	43	Bangladesh	306	Research
19	Switzerland	790	Pilot	44	Chile	281	Research
20	Saudi Arabia	770	Pilot	45	Finland	260	Research
21	Poland	630	Research	46	Romania	232	-
22	Argentina	598	Research	47	Portugal	230	Research
23	Sweden	588	Research	48	Peru	223	Research
24	Nigeria	535	Launched	49	Kazakhstan	222	Pilot
25	Belgium	516	Research	50	New Zealand	218	Proof of concept

Note: Among the top 50 countries, we use digital euro data for Germany, France, Italy, the Netherlands, Belgium, Ireland, Finland, and Portugal, as these Eurozone countries have a unified digital euro development and pilot program. Romania in Europe is not a member of the Eurozone and has not developed a CBDC by 2022. (Source: World Bank's WDI database)

Appendix D. Explanation of Indicators of Digitalization Coverage and Digitalization Level[1]

Level 1 Dimension	Level 2 Dimension	Indicators
Digitalization Coverage (Breadth of Coverage)	Account coverage rate	Number of Alipay accounts owned by per 10,000 people
		Proportion of Alipay users who have bank cards bound to their Alipay accounts
		Average number of bank cards bound to each Alipay account
Digitalization Level (Level of Digitalization)	Mobility	Proportion of number of mobile payments
		Proportion of total amount of mobile payments
	Affordability	Average loan interest rate for small & micro businesses
		Average loan interest rate for individuals
	Credit	Proportion of number of Ant Check Later payments
		Proportion of total amount Ant Check Later payment
		Proportion of number of "Zhima Credit as deposit"cases
		Proportion of total amount of "Zhima Credit as deposit"
	Convenience	Proportion of number of QR code payments by users
		Proportion of the total amount/average amount of QR code payments by users.
Source: Institute of Digital Finance, Peking University (Http://idf.pku.edu.cn)		

Appendix E. Four Types of Money in China

Composition	M0	M1	M2	M3
Physical currency in circulation (Banknotes and coins outside central banks and the vaults of depository institutions)	✓	✓	✓	✓
Demand deposits held by corporations		✓	✓	✓
Personal savings deposits		✓	✓	✓
Time deposits held by corporations			✓	✓
Commercial paper				✓
Large negotiable certificates of deposit				✓

Source: The 'Interim Measures for the Statistics and Announcement of the Money Supply (2013)' issued by The People's Bank of China. (http://www.pbc.gov.cn)

[1] Ant Financial offers a range of digital financial services including payment solutions, insurance, monetary funds, credit services, investment opportunities, and credit assessment.

Appendix F. Progress of e-CNY Pilot Testing Programs (2020-2023)

Batch	Year	Regions	Notable Developments
1st	2020	Shenzhen	Shenzhen and Suzhou made rapid progress, conducting extensive offline payment tests and establishing numerous commercial merchant systems. In Shenzhen, e-CNY does not have different denominations, patterns, or numbers but operates through a token-based balance account. Some banks have adopted the smallest denomination, eliminating the need for change, as wallet balances update automatically through the e-CNY system.
		Suzhou	In Suzhou, e-CNY was first introduced in an online e-commerce scenario through the issuance of consumption vouchers. It was later integrated into public transportation systems, including subways and buses, and used for salary and bonus payments. The "dual offline payment" test was implemented to prevent double spending.
		Chengdu	To emphasizes digital currency's role in small-value and high-frequency transactions and inclusive finance. It covers various use cases, including online and offline payments, business transactions, and retail payment.
		Xiong'an	To enhance usability, digital wallets are available in both software (mobile apps) and hardware (offline-capable devices like visual cards and wearables), supporting online and offline payments.
		Winter Olympic Venues	It plans to test e-CNY usage at the Beijing Winter Olympics venues for foreign athletes and visitors without domestic bank accounts, allowing them to transact using only a smartphone.
2nd	2021	Six cities were added to the 2nd batch.	It focused on small-value, high-frequency transactions and provided the benefit of fee-free withdrawals and transfers. The six cities involved are Shanghai, Changsha, Hainan, Qingdao, Dalian, and Xi'an.
3rd	2022	Eleven cities were added to the 3rd batch	It further explores small-value, high-frequency transactions, aiming to integrate digital currency more comprehensively into various economic sectors and daily life. The five cities involved are Tianjin, Chongqing, Guangzhou, Fuzhou, and Xiamen, while the six cities in Zhejiang Province include Hangzhou, Ningbo, Wenzhou, Huzhou, Shaoxing, and Jinhua.
4th	2023	Four entire provinces along with five new cities were added to the 4th batch.	Expanding application scenarios, increasing the user base, and building a multi-domain e-CNY payment ecosystem are key steps in integrating e-CNY into the economy. Its use has extended beyond personal consumption to public and corporate services, including salary distribution, inclusive loans, and green finance, as well as government functions such as fiscal management, taxation, public utilities, e-governance, and support for agriculture and poverty alleviation. This expansion includes four entire provinces—Guangdong, Jiangsu, Hebei, and Sichuan—along with five new cities: Jinan, Nanning, Fangchenggang, Kunming, and Xishuangbanna.

This table reports the regions where the e-CNY pilot program is being implemented. In summary, the pilot covers Hebei, Jiangsu, Guangdong, Sichuan, and Hainan provinces, as well as the cities of Shanghai, Tianjin, and Chongqing. It also includes Fujian Province (Fuzhou and Xiamen), Zhejiang Province (Hangzhou, Ningbo, Wenzhou, Huzhou, Shaoxing, Jinhua, and Yiwu), Shandong Province (Jinan and Qingdao), Liaoning Province (Dalian), Shaanxi Province (Xi'an), Hunan Province (Changsha), Guangxi Zhuang Autonomous Region (Nanning and Fangchenggang), and Yunnan Province (Kunming and Xishuangbanna Dai Autonomous Prefecture). Additionally, e-CNY was tested in the 2022 Beijing Winter Olympics scenarios.

Appendix G. The differences among e-CNY, Traditional electronic payment, and M0

Items	E-CNY	M0 (Cash)	Electronic Payments
Form	Digital	Physical	Digital
Legal status	Legal tender	Legal tender	Merely a mode of payment
Issuer	Central bank	Central bank	Commercial banks and payment service providers
Regulation	Central bank	Central bank	Various financial authorities
Liability	Liability of central bank to citizens	Liability of central bank to citizens	Liability of commercial banks and payment platforms to public
Privacy (Anonymity)	Balance anonymity and traceability	High	Low
Accessibility	Universal (requires digital access)	Universal	Requires Bank Account or Credit History
Interest bearing	Typically no	No	Potentially yes (based on account conditions)
Economic influence	Enhances the efficiency and precision of monetary policy transmission	Traditional monetary policy tool	Indirect influence through spending behavior and data generation

Appendix H. Features Overview of e-CNY

Feature/Detail	Description
Tap Payment Functionality	NFC Payment Method: Use NFC-enabled phone near POS terminal or touch two NFC-enabled phones together
Offline Payment	Enabled by the "Dual Offline" technology which allows for payments without internet
Operating Institutions	Nine institutions include the Big 6 major commercial banks, China Merchants Bank, Alipay's MyBank, and WeChat's WeBank
Accessibility	Individuals without other payment methods or short-term foreign visitors can use e-CNY without a bank account for daily payments
Integration with Services	Expected to be integrated with various services of public transport, utilities, and online marketplaces
Interoperability for Cross-border Usage	Efforts are being made for cross-border interoperability, especially with countries involved in the Belt and Road Initiative
Security	Enhanced security measures including cryptographic algorithms unique to the e-CNY. Some trials incorporated hardware wallets and wearable devices
Privacy Protection	"Controllable Anonymity" where transactions are anonymous to merchants but visible to regulators

Appendix I. Four Types of e-CNY Wallet

Wallet Type	Verification location	Required verification	Bind bank account	Real-name verification level	Transaction limits
Type I	On-site (Pilot areas)	Valid ID, phone number, domestic bank account	Yes	Highest	No limit
Type II	Remote	ID, phone number, domestic bank account	Yes	High	Not specified
Type III	Remote	ID and phone number	No	Moderate	Not specified
Type IV	Remote	Phone number only	No	Anonymous	Balance: 10,000 yuan Single: 2,000 yuan Daily: 5,000 yuan Annual: 50,000 yuan

This table presents the four e-CNY wallet types. **Type I** wallets require full identity verification, including an on-site check of official ID, phone number, and a domestic bank account, offering unrestricted transactions. **Type IV** wallets, or "anonymous wallets," require only a phone number, ensuring maximum accessibility but with the strictest transaction limits for privacy. **Type II** and **Type III** wallets fall in between, with **Type II** requiring bank account verification and offering higher limits than **Type III**, while **Type III** requires only ID and phone number verification. (Source: Digital Currency Research Institute of the People's Bank of China)

Appendix J. Variable Definitions in Chapter four

Variables	Definition
$MS\_M0_{i,t}$	Physical currency in circulation scaled by GDP in province *i* in year *t*, which is estimated with the provincial bank branches data.
$MD\_CashWithdrawal_{i,t}$	The amount of cash withdrawal scaled by GDP in province *i* in year *t*, which is estimated with the provincial bank branches data.
$Digitalization\ Coverage_{i,t}$	Breadth of digitalization coverage index issued by Peking University.
$Digitalization\ Level_{i,t}$	Digitalization level index issued by Peking University.
$Mobile\_Phone_{i,t}$	Mobile phone penetration rate, measured by the number of mobile phones 100 people.
$E\text{-}commerce_{i,t}$	Per capita amount of e-commerce transaction volume.
$GDPG_{i,t}$	The growth rate of GDP of province *i* in year *t*.
$Population_{i,t}$	Natural logarithm of the population of province *i* in year *t*.
$Education_{i,t}$	Per capita years of education for citizens of province *i* in year *t*.
$OADR_{i,t}$	Old-age Dependency Ratio for province *i* in year *t*, defined as the ratio of individuals aged 65 and over to the total population.
$CPI_{i,t}$	Natural logarithm of the consumer price index for province *i* in year *t*.

Appendix K. List of Abbreviations

AMM = Automatic Market Maker

BTC = Bitcoin

CBDC = Central Bank Digital Currency

CBDCs = Central Bank Digital Currencies

CEXes = Centralized Digital Exchanges

DeFi = Decentralized finance

DEXes = Decentralized Digital Exchanges

e-CNY = Digital Chinese Yuan

EOS = Enterprise Operating System

ETH = Ethereum

ICOs = Initial Coin Offerings

RMB = Chinese Yuan

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