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Review Article

TECHNOLOGY, REGULATION, AND THE DIVERGENT TRAJECTORIES OF RETAIL AND CROSS-BORDER CENTRAL BANK DIGITAL CURRENCY

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ABSTRACT

Background. Central bank digital currency (CBDC) sits where fast-moving cryptographic and ledger technology meets fast-moving regulation, yet the two are usually studied separately, and retail and cross-border uses are usually treated as one object. Between 2024 and 2026 major jurisdictions made sharply different regulatory choices.
Research Purpose. This review examines how advanced cryptographic solutions and hybrid blockchain architectures interact with evolving regulatory frameworks to shape economic outcomes and user adoption, and how that interaction differs between retail and cross-border implementations.
Research Method. We conduct a critical review. A Scopus search on 8 October 2026 (1,418 records, 1,045 retained) maps the field, and a purposive selection of peer-reviewed studies and official publications is synthesised around four research questions.
Findings. Technology and regulation terms co-occur at about the level expected by chance, and evidence on cryptographic feasibility and on adoption comes largely from separate literatures. Hybrid, two-tier architectures dominate, and the tension between privacy and anti-money laundering is increasingly handled through cryptographic design. Retail adoption is weak in every live system reviewed, while wholesale cross-border arrangements show the clearest technological value but are limited by governance. Regulatory choices since 2024 now shape outcomes more than technical feasibility does.
Conclusion. Technology and regulation co-evolve, and retail and cross-border CBDC face different binding constraints. We offer a co-evolution framework with four falsifiable propositions and argue that CBDC should be studied together with regulated stablecoins and tokenised deposits.

Keywords: Central bank digital currency, Cross-border payments, Distributed ledger technology, Financial regulation, Privacy-enhancing technologies.

BACKGROUND

Within a decade, central banks moved from conceptual discussion of central bank digital currency (CBDC) [1, 2] to proofs of concept, pilots and, in a small number of jurisdictions, live issuance. Successive surveys by the Bank for International Settlements (BIS) show that most central banks now engage in some form of CBDC work [3, 4]. In the 2024 survey, 91 per cent of the 93 responding central banks were exploring a retail CBDC, a wholesale CBDC or both, wholesale work was at more advanced stages, and more than one in three had accelerated CBDC work in response to stablecoins and other cryptoassets [5]. The Atlantic Council's CBDC tracker records 146 countries and currency unions, representing over 98 per cent of global gross domestic product (GDP), exploring a CBDC

as of May 2026, up from 87 in May 2022. Of these, 77 are in development, pilot or launch, and every G20 economy except the United States is among them [6]. Retail CBDCs have been issued in The Bahamas (the Sand Dollar, launched in 2020), the Eastern Caribbean Currency Union (DCash, launched in 2021), Nigeria (the eNaira, launched in 2021) and Jamaica (JAM-DEX, launched in 2022) [7, 8], of which the tracker currently counts three (The Bahamas, Jamaica and Nigeria) as fully launched [6]. China's e-CNY has operated as the largest retail pilot among major economies [9].

Two forces drive this transformation. The first is technological. Advances in applied cryptography (blind signatures, zero-knowledge techniques, secure hardware and post-quantum schemes) and in permissioned distributed-ledger and unified-ledger architectures make privacy-preserving, programmable and interoperable public money technically conceivable [10, 11, 12]. The second is institutional: the decline of cash in some economies, the rise of private stablecoins, concerns about monetary sovereignty and strategic competition over cross-border payment rails [13, 14]. Between 2024 and 2026 these forces produced sharply divergent policy choices. The United States prohibited federal agencies from establishing or promoting a CBDC and enacted a federal framework for payment stablecoins [15, 16]. The European Central Bank (ECB) completed the preparation phase of the digital euro and moved to the next phase, conditional on legislation [17]. The BIS stepped back from the multi-CBDC platform mBridge, which has since been led by its participating central banks [18]. China redesigned the e-CNY from January 2026 so that wallet balances become interest-bearing liabilities of commercial banks, a change that arguably moves much of the e-CNY away from the conventional definition of CBDC [19].

The review literature on CBDC is already substantial, but to our reading it leaves a specific gap. Broad surveys map motives, design options and research frontiers [13, 20, 21]. Thematic and critical reviews synthesise economic debates [22, 23], and bibliometric work charts the growth of the field [24]. These contributions are valuable, yet they largely (a) treat CBDC as a single construct rather than separating retail from cross-border use cases, (b) survey technology and regulation as parallel themes rather than theorising their interaction, and (c) were completed before the regulatory developments of 2024 to 2026 had played out. This review addresses all three limitations.

We first fix terms. A CBDC is a digital form of central bank money that differs from balances in traditional reserve or settlement accounts [2]. The literature distinguishes retail (general-purpose) CBDC, available to households and firms, from wholesale CBDC, restricted to financial institutions for interbank settlement [1, 2]. Cross-border CBDC is not a third type of instrument but a use case that spans both; in practice it is concentrated in wholesale multi-CBDC arrangements [25]. Access can be token-based, where validity is verified cryptographically in a bearer-like manner, or account-based, where transfers are tied to verified identities [11]. A group of seven central banks and the BIS summarised three foundational principles for any CBDC: it should do no harm to monetary and financial stability, it should coexist with cash and other forms of money, and it should promote innovation and efficiency [26].

Auer and Böhme's [11] CBDC pyramid is the field's organising design taxonomy. It derives a hierarchy of technical choices from consumer needs: the operational architecture (a direct claim operated by the central bank, an indirect or synthetic claim on intermediaries, or a hybrid or intermediated model), the infrastructure (conventional or distributed ledger), the access model (account or token) and the degree of cross-border interlinkage. A comparative review of central bank projects finds that hybrid and intermediated architectures dominate, that no surveyed central bank favoured a purely

indirect design, and that distributed ledger technology (DLT) is common in proofs of concept even where production systems may not rely on it [27]. Allen et al. [10] show that most CBDC goals can be met without a blockchain and that the architectural choice is ultimately a trade-off among privacy, resilience, performance and governance.

For cross-border payments, Auer et al. [25] classify multi-CBDC arrangements into three models of increasing integration: compatible national systems that share standards, interlinked systems connected through technical interfaces or common clearing, and a single multi-currency system operated jointly. Each successive model promises greater efficiency but requires participants to cede more control over governance, access and data. This integration-sovereignty trade-off sits alongside the G20 targets for cheaper, faster, more transparent and more accessible cross-border payments [28].

Four bodies of theory inform our synthesis. Monetary-banking theory, anchored in the bank-run model of Diamond and Dybvig [29] and the equivalence result of Brunnermeier and Niepelt [30], frames questions of disintermediation and stability. Technology-acceptance theory, notably the technology acceptance model [31] and the unified theory of acceptance and use of technology [32], frames individual adoption. Information-privacy theory, including privacy-calculus and antecedents-privacy concerns-outcomes models, frames the privacy-adoption link [33, 34]. Institutional and international political-economy perspectives on monetary sovereignty frame the cross-border dimension [14].

The review is organised around the framework in Figure 1. Technology (cryptography and ledger architecture) and regulation (legal and policy constraints) form a jointly determined CBDC design regime whose components influence each other reciprocally. The design regime shapes two outcome domains, economic outcomes and user adoption, which feed back into one another and, through policy learning, into regulation. The use case (retail or cross-border) moderates the relationship between design and outcomes. The propositions marked in the figure are developed in the Discussions.

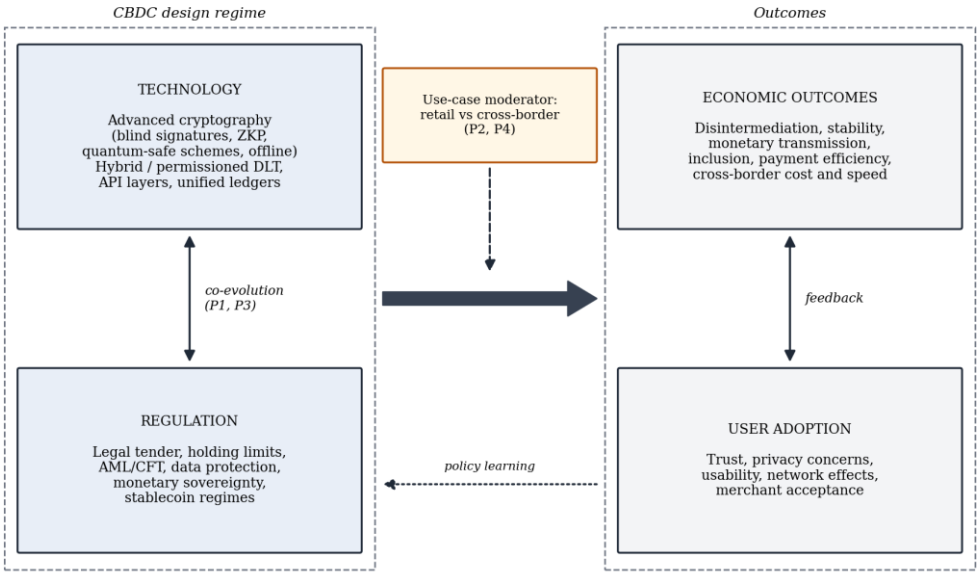


Figure 1. Technology-regulation co-evolution framework for CBDC outcomes. P1 to P4 refer to the propositions in the Discussions. Source: authors' elaboration.

The aim of this review is to examine how advanced cryptographic solutions and hybrid blockchain architectures interact with evolving regulatory frameworks to shape the economic outcomes and user adoption of CBDC, and to show how that interaction differs between retail and cross-border implementations.

To meet this aim, the review addresses one main research question and four sub-questions. The main research question is: how do emerging technological frameworks (advanced cryptographic solutions and hybrid blockchain models) interact with evolving regulatory frameworks to shape the economic outcomes and user adoption of CBDC, and how does this interaction differ between retail and cross-border implementations? The first research question asks which advanced cryptographic and privacy-by-design solutions have been proposed or tested, and how they reconcile privacy with anti-money laundering and countering the financing of terrorism (AML/CFT) and data-protection requirements. The second research question asks how hybrid, permissioned and unified-ledger architectures compare with centralised designs on interoperability, programmability and resilience, and which regulatory constraints select among them. The third research question asks how legal and regulatory frameworks (legal tender, holding limits, monetary sovereignty, cross-border governance and stablecoin regimes) co-evolve with technical design. The fourth research question asks what economic outcomes and adoption patterns the evidence shows, and how they differ between retail and cross-border settings.

The review makes three contributions. First, it combines a documented map of 1,045 Scopus-indexed records with a critical synthesis of peer-reviewed and institutional evidence up to October 2026. Second, it develops an integrative technology-regulation co-evolution framework with falsifiable propositions. Third, it offers a structured retail-versus-cross-border contrast that is consistent with reading the retail adoption puzzle as a mismatch between instrument and use case rather than as a failure of technology. We state this reading as a proposition to be tested, not as an established result.

RESEARCH METHOD

This study is a critical review [35]. A critical review goes beyond describing the literature: it evaluates the contribution of key sources and integrates them into a conceptual model. The design suits the research questions for three reasons. First, the evidence is heterogeneous, spanning theoretical models, engineering prototypes, legal analyses and adoption surveys, which rules out pooling effect sizes. Second, much of the decisive evidence on cryptography and cross-border arrangements is produced by central banks and the BIS rather than in journals. Third, the aim is conceptual integration, a framework and falsifiable propositions, rather than an estimate of effects [36]. A critical review does not claim the exhaustiveness or replicability of a systematic review. The documented search below maps the boundaries of the field and informs a purposive selection of sources; it is not a substitute for a protocol-driven systematic search.

To situate the review in the wider literature, we searched Scopus on 8 October 2026 with the string in Table 1. Scopus is a large curated multidisciplinary abstract and citation database and one of the search systems evaluated as suitable for use as a principal source in evidence syntheses [37]. The search returned 1,418 records published between 2016 and 2026. After removing 3 duplicates and 370 records of ineligible document types (274 book chapters, 54 books, 27 conference reviews, 7 editorials, 4 notes, 2 errata, 1 letter and 1 retracted item), 1,045 records remained. This corpus is used to map publication trends and research themes and as the main pool from which peer-reviewed studies were drawn. We did not search Web of Science because institutional access was not available. Institutional

evidence was gathered from official publications of the BIS (including BIS Innovation Hub project reports), the Committee on Payments and Market Infrastructures (CPMI), the International Monetary Fund (IMF), the Financial Stability Board (FSB), the ECB, the European Parliament, the Board of Governors of the Federal Reserve System and regional Reserve Banks, the Bank of England, the People's Bank of China (PBoC), the Reserve Bank of India, the Central Bank of Nigeria, the Central Bank of The Bahamas, the Eastern Caribbean Central Bank and Bank Indonesia. Policy analysis from the Atlantic Council and the Peterson Institute for International Economics was admitted only for recent factual developments not yet covered by peer-reviewed work. We also followed the reference lists of key sources to identify influential studies outside the Scopus corpus.

Table 1. Scopus search string and source selection criteria

Element	Specification
Database and search string	Scopus, title, abstract and keywords: TITLE-ABS-KEY (("central bank digital currenc*" OR "CBDC*" OR "digital euro" OR "digital pound" OR "e-CNY" OR "digital yuan" OR "eNaira" OR "sand dollar" OR "e-rupee" OR "digital rupee" OR "digital rupiah") AND ("cryptograph*" OR "zero-knowledge" OR "blind signature*" OR "privacy" OR "blockchain" OR "distributed ledger" OR "DLT" OR "architecture" OR "interoperab*" OR "programmab*" OR "regulat*" OR "legal tender" OR "anti-money laundering" OR "adoption" OR "cross-border" OR "wholesale" OR "retail" OR "financial stability" OR "disintermediation")) AND PUBYEAR > 2015 AND PUBYEAR < 2027 AND LANGUAGE (english)
Records	1,418 retrieved on 8 October 2026; 1,045 after removal of duplicates and ineligible document types
Period and language	Included: published 1 January 2016 to 8 October 2026, in English. Excluded: published before 2016 or in other languages
Topic	Included: substantive analysis of CBDC design, cryptography, architecture, regulation, economic effects or adoption. Excluded: cryptocurrency or stablecoin studies that do not address CBDC; passing mentions of CBDC
Source type	Included: peer-reviewed journal articles, reviews and conference papers; central bank, BIS, IMF, FSB and other official reports issued by the institutions themselves. Excluded: books, book chapters, editorials, notes, letters, errata, retracted items and proceedings front matter; opinion pieces without analysis; non-authoritative web content
Evidence type	Included: theoretical models, empirical studies, prototypes, case studies and legal analyses. Excluded: duplicate reports of the same study (the most complete version retained)

Sources for the synthesis were selected purposively against the criteria in Table 1. Within the eligible pool, selection weighed four considerations: relevance to at least one research question; influence, judged by publication venue and citations; methodological transparency; and, for regulatory developments, recency. We sought coverage of both retail and cross-border settings deliberately, to support the comparison at the centre of the review. Where a study existed both as a working paper and as a journal article, we preferred the peer-reviewed version. Conference papers were eligible because peer-reviewed proceedings are a principal venue for applied cryptography, which is central to the first research question; books and book chapters were not, because their peer-review status cannot be verified consistently. The reference list comprises 71 sources: 29 peer-reviewed journal articles or conference chapters, 17 working papers, research briefs and central bank series, 22 official reports, press releases and legal texts, and 3 policy analyses.

Institutional sources were limited to official publications of central banks, international financial institutions and European Union institutions, and we compared their

claims with independent peer-reviewed analysis wherever such analysis existed. Central banks and the BIS are both actors in CBDC development and the main producers of evidence on it, so we attribute their claims explicitly in the text. We integrated the selected evidence through a framework synthesis: findings were mapped onto the nodes and links of Figure 1 and combined narratively by research question, with an explicit retail-versus-cross-border comparison. Tables 2 to 4 summarise the principal sources by type, method and main finding. Finally, to describe the retained Scopus records, we classified them by keyword families (technological, regulatory, adoption, economic outcome, and cross-border or wholesale) applied to titles, abstracts and author keywords. This is a descriptive device, and its limits are set out in the Findings and Discussions.

FINDINGS

Mapping the literature

The Scopus corpus shows a young and fast-growing field. Of the 1,418 records retrieved, annual counts rose from 4 in 2016 to 36 in 2020 and 337 in 2025, and 318 records had already been published in 2026 by the search date (Figure 2). Among the 1,045 retained records, 790 are journal articles, 210 conference papers, 43 reviews and 2 short surveys. The most frequent outlets are the Journal of Payments Strategy and Systems (48 records), Lecture Notes in Networks and Systems (23) and Research in International Business and Finance (20). Citation counts remain low (median 2), as expected for recent literature.

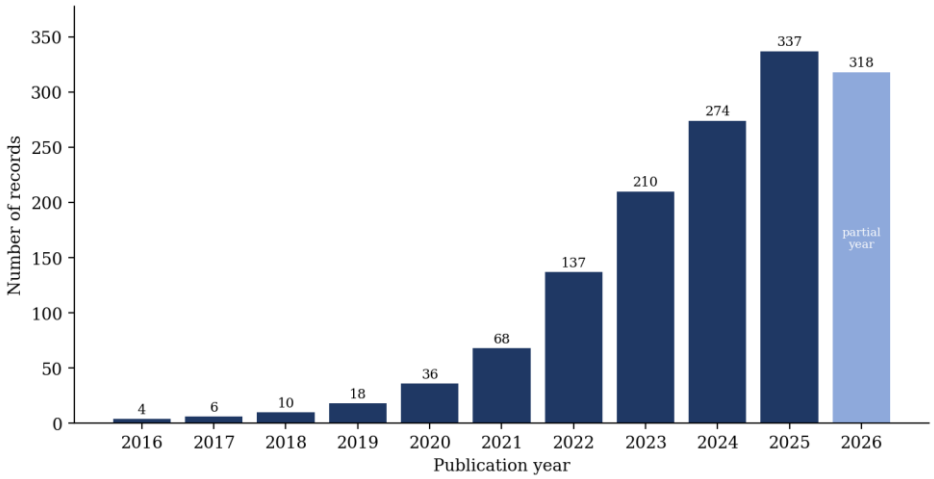


Figure 2. Scopus records by publication year, 2016 to 2026 (n = 1,418, before removal of duplicates and ineligible document types; the 2026 bar covers records published up to the search date of 8 October 2026).

The keyword classification shows how attention is distributed across the 1,045 retained records. Regulatory and legal terms appear in 51.5 per cent of records, technological terms in 46.9 per cent, adoption-related terms in 42.2 per cent and economic-outcome terms in 37.0 per cent. Cross-border and wholesale terms appear in 16.7 per cent of records overall, but their share rose from 9.0 per cent before 2022 to 17.7 per cent from 2022 onwards, consistent with the shift of central bank experimentation towards wholesale arrangements [5]. Technological and regulatory terms co-occur in 25.0 per cent of records. This figure is not evidence that the two strands are studied apart: if the two families of terms were statistically independent, we would expect about 24.2 per cent of records (0.469×0.515) to contain both, so the observed co-occurrence is close to the chance level. Two further cautions apply. The classification is by keyword and not by reading, and the search string itself contains terms from both families, so every retained record already

carries some of them. We therefore treat these shares as a description of the retrieved corpus, not as a measure of integration, and we rest our claim about limited integration on the qualitative reading that follows.

Qualitatively, the sources we selected fall into three methodological clusters. The first comprises theoretical macro-finance models of disintermediation, bank runs and optimal design (for example [30, 38, 39, 40]). The second comprises empirical adoption studies, typically surveys grounded in technology-acceptance, trust or privacy-calculus theory (for example [33, 34, 41]). The third comprises design, prototype and case-study work, dominated by central bank and BIS Innovation Hub reports (for example [7, 8, 42, 43]). This division of labour is itself a finding. Evidence on cryptographic feasibility and cross-border architecture comes overwhelmingly from institutional experimentation, whereas evidence on adoption comes overwhelmingly from academic surveys of intentions, and among the sources we selected few studies bring the two together.

Advanced cryptography and privacy-by-design (first research question)

The intellectual lineage of privacy-preserving digital money runs from the blind signatures of Chaum [44], which allow a bank to sign a token without seeing its serial number, to contemporary CBDC proposals. Chaum et al. [45] propose a token-based, software-only CBDC that uses blind signatures without DLT, preserves transaction privacy for payers while keeping payees identifiable for AML and tax purposes, and offers protection against systemic privacy risk from future quantum attacks. They argue that such a design replicates cash rather than deposits and therefore leaves monetary policy and financial stability largely unaffected.

The most consequential empirical test of this lineage is the BIS Innovation Hub's Project Tourbillon [42]. Tourbillon built two prototypes based on the eCash design. The first offered unconditional payer anonymity: a consumer paying a merchant discloses no personal information to the merchant, the banks or the central bank, while the merchant's identity is disclosed to the merchant's bank and the central bank observes CBDC circulation only in aggregate. The second prototype strengthened protection against, and detection of, counterfeiting. The project showed that payer anonymity and scalability are feasible, but that strict privacy and strict security cannot both be maximised. It also implemented quantum-safe blind signatures, which increased payment duration by a factor of five and reduced throughput by a factor of 200 relative to conventional cryptography [42]. None of this required a blockchain.

A wider set of privacy-enhancing technologies has been mapped for CBDC, including selective disclosure, zero-knowledge techniques, secure hardware for offline payments and anonymity-preserving value limits [46]. Pocher and Veneris [47] frame the problem as regulation-by-design: AML/CFT rules are embedded in the protocol so that transparency is available to authorities under defined conditions while ordinary payments remain private. The ECB's offline digital euro concept applies similar reasoning at the policy level, promising cash-like privacy for proximity payments made offline [17]. The counterweight in the literature is the concern that CBDC could become an instrument of surveillance and control, a digital Leviathan, if privacy is not constitutionally protected [48].

The synthesis yields a clear interaction result for the first research question. Cryptography in CBDC is not neutral plumbing. Each scheme is engineered to satisfy a specific regulatory constraint (AML/CFT accountability, data-protection law, counterfeiting resistance or long-term quantum resilience), and the resulting trade-offs (privacy against security, security against performance) are resolved by policy choice. This

is the clearest micro-level evidence of technology-regulation co-design, although the evidence concerns feasibility in prototypes and not outcomes in live systems.

Hybrid architectures, DLT and interoperability (second research question)

For retail CBDC, the modal architecture is hybrid and intermediated [11, 27]. The e-CNY was explicitly designed as a two-tier system in which the PBoC issues the currency and authorised operators handle distribution and customer services, combining centralised management with selective use of distributed technology [9, 49, 50]. The BIS Innovation Hub's Project Rosalind, conducted with the Bank of England, operationalised the two-tier model through an application programming interface (API) layer between a central bank ledger and private service providers. It developed 33 API functionalities and tested more than 30 retail use cases, including programmable and offline payments [43]. The design logic is to keep the base money simple and neutral while allowing innovation, including programmability, in the private service layer.

For wholesale and cross-border CBDC, the architectural debate shifts to shared and unified ledgers. The BIS proposes a unified ledger combining tokenised central bank reserves, tokenised commercial bank deposits and other tokenised assets on a common programmable platform, preserving the singleness of money while enabling atomic settlement [12]. Project Agorá, announced in 2024, tests this concept for wholesale cross-border payments with seven central banks (the Bank of France on behalf of the Eurosystem, the Bank of Japan, the Bank of Korea, the Bank of Mexico, the Swiss National Bank, the Bank of England and the Federal Reserve Bank of New York) and a large group of private financial institutions [51]. Project mBridge, a single multi-currency system on a permissioned DLT platform shared by the central banks of mainland China, Hong Kong SAR, Thailand and the United Arab Emirates, reached minimum viable product stage in 2024, when the Saudi Central Bank also joined [52].

Regulatory and governance concerns select among these designs. Programmability raises concerns about the fungibility and singleness of money when conditions are attached to the base asset rather than to services built on it. Interoperability raises concerns about capital-flow management, data sharing and sovereignty that grow with the degree of integration [25]. The most striking recent example of regulation reshaping architecture is the redesign of the e-CNY. To remove the risk that e-CNY adoption would drain bank deposits, balances held in commercial bank wallets have, since 1 January 2026, been treated as interest-bearing commercial bank liabilities covered by deposit insurance, with the PBoC retaining infrastructure and standard-setting roles [19]. A stability constraint thus transformed the technical and legal nature of the instrument.

Regulatory frameworks and their co-evolution with technology (third research question)

Legal foundations come first. Many central bank laws were not drafted with a general-purpose digital liability in mind, which raises questions about issuing authority, legal tender status, the treatment of tokens as currency and the applicability of AML and data-protection regimes [53]. The answers that jurisdictions gave between 2024 and 2026 produced three distinct regulatory trajectories.

The first trajectory is prohibition of a retail CBDC combined with regulated private digital money, exemplified by the United States. Executive Order No. 14178 [15] prohibited federal agencies from establishing, issuing or promoting a CBDC. The House of Representatives passed the Anti-CBDC Surveillance State Act in July 2025 [54], and the GENIUS Act, signed on 18 July 2025, created a federal framework for payment

stablecoins that, among other provisions, bars issuers from paying interest [16, 19]. This is a deliberate choice to rely on regulated private digital dollars rather than public digital money. It was preceded by a Federal Reserve discussion paper that set out the potential benefits and risks of a US CBDC without taking a position [55].

The second trajectory is cautious public money with statutory safeguards, exemplified by the euro area and the United Kingdom. The European Commission's [56] legislative proposal would give the digital euro legal tender status, empower the ECB to set holding limits and embed privacy protections, including an offline mode. The ECB concluded its preparation phase in October 2025, and its Governing Council decided to move to the next phase, with possible first issuance in 2029 conditional on the adoption of the regulation [17]. In July 2026 the European Parliament adopted its negotiating position by 416 votes to 169, endorsing a digital euro that works online and offline, with built-in privacy safeguards, a cap on individual holdings and an acceptance obligation for most businesses, and opened negotiations with the Council [57]. Holding limits and non-remuneration, informed by earlier proposals for tiered remuneration [58], are the principal regulatory instruments for containing disintermediation risk. In the United Kingdom, the Bank of England and HM Treasury [59] reported on a consultation that drew more than 50,000 responses and committed to primary legislation guaranteeing users' privacy before any launch. Their March 2026 progress update places the digital pound still in its design phase, with the decision on whether to proceed to be announced in 2026 [60].

The third trajectory is state-directed rollout, exemplified by China and India. The PBoC expanded the e-CNY through pilots, incentives and integration with existing platforms before redesigning it in 2026 [9, 19]. The Reserve Bank of India [61] extended its retail pilot with offline and programmability features and allowed certain non-banks to offer CBDC wallets. Indonesia illustrates a sequenced variant. Bank Indonesia's [62] Project Garuda sets out a phased path that begins with a wholesale digital rupiah before any retail extension, and in December 2024 the central bank announced that the proof of concept for the wholesale digital rupiah cash ledger, the immediate stage of the project, had met all its test scenarios on the DLT platforms tested [63].

Across the three trajectories, regulation appears to be the binding constraint on whether and how a retail CBDC is issued. Where regulation prohibits, technical capability is irrelevant to retail issuance. Where regulation enables cautiously, design is shaped around statutory privacy and stability safeguards. Where the state directs, adoption is pursued administratively and, as the Chinese redesign shows, the design itself is revised when stability concerns dominate.

Economic outcomes (fourth research question, first part)

The theoretical core of the literature concerns bank disintermediation and financial stability, and Table 2 lists the principal sources on design and economic outcomes. Brunnermeier and Niepelt [30] establish an equivalence result: if the central bank passes CBDC-funded balances back to banks, the introduction of CBDC need not change equilibrium allocations. Fernández-Villaverde et al. [39] extend a Diamond-Dybvig framework and show that in normal times a CBDC can replicate the allocation achieved by private intermediation, while in a panic the central bank's more rigid contract can deter runs, with the risk that the central bank becomes a deposit monopolist that crowds out private credit. Keister and Sanches [40] show that CBDC can improve the efficiency of exchange but may crowd out bank deposits, raise banks' funding costs and reduce investment, so the optimal design balances these effects. In contrast, when banks have market power, an interest-bearing CBDC can raise deposit rates and even expand lending

within a range of CBDC rates [64, 65]. Agur et al. [38] show that design parameters, notably remuneration and the degree of anonymity, determine whether CBDC competes more with cash or with deposits. Together these results motivate the holding limits, tiered or zero remuneration and intermediated distribution observed in practice [17, 58].

Other economic outcomes receive less rigorous evidence. Financial inclusion was an explicit objective of the eNaira [8] and a supplementary objective in the Caribbean, where the main goal was to shift cash-based economies towards digital payments [7]. Payment efficiency and the cost and speed of cross-border payments constitute the strongest positive case, but that evidence comes largely from wholesale experimentation measured against the FSB's [28] targets and not from independent evaluation. Monetary sovereignty and currency substitution frame the international dimension. CBDC can reinforce effective monetary sovereignty [14], but cross-border access to foreign CBDCs could also facilitate currency substitution in economies with weak currencies [13].

Table 2. Principal sources on design, architecture and economic outcomes (first, second and fourth research questions)

Source	Type or method	Key finding
Auer and Böhme [11]	BIS Quarterly Review; conceptual taxonomy	CBDC pyramid linking consumer needs to architecture, infrastructure, access and interlinkage
Auer et al. [27]	BIS working paper; comparative review of projects	Hybrid and intermediated architectures dominate; DLT common in proofs of concept
Allen et al. [10]	NBER working paper; design analysis	Most CBDC goals achievable without blockchain; design is a trade-off among privacy, resilience and performance
Chaum et al. [45]	SNB working paper; cryptographic design	Token-based, blind-signature CBDC with payer privacy, payee accountability and quantum-resistant privacy
BIS [42] (Tourbillon)	BIS Innovation Hub report; prototypes and scalability tests	Payer anonymity feasible; privacy-security trade-off; quantum-safe signatures cut throughput by a factor of 200
BIS [43] (Rosalind)	BIS Innovation Hub; API prototype	33 API functionalities and more than 30 retail use cases; programmability kept in the service layer
Auer et al. [46]	Communications of the ACM; conceptual mapping	Maps privacy-enhancing technologies and design options for CBDC
Pocher and Veneris [47]	IEEE TNSM; regulation-by-design scheme	Embeds AML/CFT rules into protocol design to reconcile privacy and transparency
BIS [12]	BIS Annual Economic Report; conceptual	Unified ledger combining tokenised reserves and deposits preserves singleness of money
Brunnermeier and Niepelt [30]	Equivalence theory	CBDC need not change allocations if CBDC-funded balances are passed back to banks
Fernández-Villaverde et al. [39]	Diamond-Dybvig model	CBDC can deter runs but risks a central bank deposit monopoly that crowds out credit
Andolfatto [64]	Monetary model with monopoly banking	Interest-bearing CBDC can raise deposit rates and inclusion without reducing lending
Chiu et al. [65]	Theory and quantitative assessment	With bank market power, CBDC within a range of rates can expand lending and output
Keister and Sanches [40]	General equilibrium model	CBDC improves efficiency of exchange but can crowd out deposits and raise bank funding costs

Source	Type or method	Key finding
Agur et al. [38]	Optimal design model	Remuneration and anonymity determine substitution with cash versus deposits
Bindseil [58]	ECB working paper; policy design	Tiered remuneration can control CBDC demand and disintermediation risk

User adoption (fourth research question, second part)

The adoption evidence is the most consistent empirical regularity in the review, and for retail CBDC it is consistently disappointing (Table 3). An IMF assessment found eNaira take-up very low: retail wallets equivalent to less than 1 per cent of bank accounts, with about 98.5 per cent of wallets unused in any given week [8]. In The Bahamas, the Sand Dollar had about 104,664 consumer wallets and about 1,500 merchant wallets in May 2023, and even after promotional campaigns its circulation amounted to only about 0.19 per cent of currency in circulation in September 2023 [7]. Noll [7] draws three lessons from the Caribbean experience that are central to this review: the underlying technology of a retail CBDC appears to have little effect on adoption, a CBDC must demonstrate value added to attract users, and it must be integrated into the wider financial ecosystem.

Table 3. Adoption evidence from live systems and individual-level studies (fourth research question)

Source	Setting and method	Key finding
Ree [8]	eNaira, Nigeria; IMF assessment	Wallets equivalent to less than 1% of bank accounts; about 98.5% of wallets unused in any given week
Noll [7]	Sand Dollar, DCash, JAM-DEX; case review	Sand Dollar circulation about 0.19% of currency (September 2023); technology has little effect on adoption
Chorzempa [19]	e-CNY; analysis of PBoC data	16.7 trillion yuan cumulative by November 2025, but only about 0.2% of 2024 card and platform payments
Reserve Bank of India [61]	e-rupee; annual report	About six million retail pilot users across 17 banks by March 2025; offline and programmable features added
Tronnier et al. [33]	Digital euro, Germany; survey	Privacy concerns reduce adoption intention; soft trust factors shape concerns and intention
Tronnier and Qiu [34]	e-CNY, China; survey (n = 682) of actual usage	Perceived vulnerabilities raise privacy concerns, which reduce usage; no privacy paradox
Solberg Söilen and Benhayoun [66]	Household survey	Institutional trust is a key determinant of CBDC acceptance
Gupta et al. [41]	Survey	Perceived risks and benefits influence trust and willingness to adopt CBDC
Sun and Rizaldy [70]	Asian e-money schemes; IMF working paper	Trust, convenience, efficiency and security drive adoption; provider incentives matter

The large economies show the same pattern at scale. The PBoC reports that the e-CNY had processed almost 3.5 billion transactions worth 16.7 trillion yuan cumulatively by November 2025, yet e-CNY transactions in 2024 amounted to only about 0.2 per cent of payments made through bank cards and digital platforms such as Alipay and WeChat Pay [19]. India's retail pilot reached about six million users across 17 banks by March 2025 [61], a modest figure next to the Unified Payments Interface, which the same report credits with 48.5 per cent of global real-time payment volume. In both cases an entrenched

and efficient incumbent payment ecosystem leaves little room for a new instrument to improve on the status quo, although we note that this is our interpretation of the descriptive data and not a tested causal claim.

Individual-level studies point to trust and privacy as the gating factors. In Germany, Tronnier et al. [33] find that privacy concerns reduce the intention to adopt a digital euro and that soft trust factors such as the credibility and image of the issuer shape both privacy concerns and intention. Studying actual e-CNY usage among 682 Chinese participants, Tronnier and Qiu [34] find that perceived vulnerabilities drive privacy concerns, which in turn reduce usage, and that no privacy paradox is observable for CBDC. Institutional trust [66], perceived risks and benefits [41], dissatisfaction with the privacy of existing payment methods combined with task-technology fit [67] and comparisons with cryptocurrencies [68] are further significant determinants, and Dutch survey evidence examines which design features would trigger consumer adoption [69]. Drawing on Asian e-money schemes, Sun and Rizaldy [70] identify trust, convenience, efficiency and security as drivers of adoption and stress the incentives faced by payment providers. The consistent message is that trust and privacy, together with a clear value proposition relative to incumbents, gate retail adoption, whereas raw technical functionality does not. Most of this evidence rests on stated intentions, whereas Tronnier and Qiu [34] examine actual usage.

Retail versus cross-border: a structured contrast

Table 4 draws the strands together. In retail settings, technology is sufficiently mature, and the binding constraints lie on the demand side (trust, privacy, incumbent competition and merchant integration) and in politics (prohibition or statutory limits). Cryptography is deployed chiefly to win trust, and regulation chiefly to contain stability risk. In cross-border settings, technology delivers its clearest value, notably atomic settlement and shorter correspondent chains [12, 25], although this evidence comes largely from the experiments of the institutions promoting these designs. The binding constraint there is governance.

Table 4. Retail versus cross-border CBDC: structured contrast

Dimension	Retail CBDC	Cross-border and wholesale CBDC
Technological maturity	Sufficient; privacy and offline designs proven in prototypes	Sufficient for atomic settlement on shared or unified ledgers
Binding constraint	Demand side (trust, privacy, incumbents) and politics	Governance (sovereignty, sanctions, standards, data sharing)
Role of cryptography	Build trust through privacy (payer anonymity, offline)	Secure multi-party settlement and compliance data
Role of regulation	Contain stability risk (holding limits, remuneration) and protect privacy	Allocate control among participating central banks
Dominant architecture	Hybrid, intermediated, two-tier; API layer	Single multi-currency platform or unified ledger
Observed outcome	Weak adoption in every live system reviewed	Growing but concentrated volumes; separation into groups of participants
Key sources	[7, 8, 34]	[18, 25, 51]

mBridge illustrates both sides. According to Atlantic Council data reported in January 2026, early pilots processed 164 transactions worth roughly USD 22 million, whereas by late 2025 the platform had processed more than 4,000 cross-border transactions with a cumulative value of about USD 55.5 billion, of which about 95 per cent of settlement volume was in e-CNY [18]. mBridge is one of 13 cross-border wholesale

CBDC projects recorded by the Atlantic Council [6], a number that has more than doubled since the G7 sanctions response to Russia's invasion of Ukraine. Yet this growth followed the BIS's decision in October 2024 to step back from direct involvement [18], and the platform now operates alongside, rather than together with, the separate Agorá initiative [19, 51]. Measured against global payment flows, mBridge volumes also remain small [19], and the concentration in a single currency raises the question of how far the platform is multilateral in practice.

DISCUSSIONS

Propositions

The synthesis supports a co-evolutionary account in which CBDC outcomes depend on the fit between technical design and regulatory constraints, and in which the best fit differs by use case. Four propositions follow. We state them as falsifiable conjectures with observable implications, not as established results, because the evidence base is mostly descriptive.

Proposition 1 (co-design): Among comparable jurisdictions, CBDC designs whose cryptographic and architectural features are specified to satisfy named regulatory constraints (AML/CFT accountability, data protection, holding limits) achieve higher adoption and smaller deposit outflows than designs in which compliance is added after the technical design. Tourbillon [42] and regulation-by-design schemes [47] show that such designs are feasible, but no study we found compares their outcomes with those of alternatives. The proposition would be weakened if adoption and deposit flows were unrelated to statutory privacy guarantees and holding-limit design once the incumbent payment ecosystem is held constant.

Proposition 2 (use-case asymmetry): The marginal effect of privacy-enhancing cryptography and statutory privacy guarantees on outcomes is larger in retail settings, where adoption is gated by trust, whereas the marginal effect of institutional design (membership, rule-making, data sharing and dispute resolution) is larger in cross-border settings. The retail half is supported by survey evidence [33, 34] and the cross-border half only by the descriptive trajectory of mBridge [18]. The proposition would be weakened if privacy features moved cross-border volumes as much as they move retail adoption, or if governance changes left retail adoption unchanged while shifting wholesale participation.

Proposition 3 (programmability paradox): Retail trust follows an inverted U in the degree to which programmability is applied to the base money: functional value rises with programmability, but beyond a threshold the perceived singleness and fungibility of money erode and surveillance concerns grow. Designs that confine programmability to the private service layer, as in Project Rosalind's API model [43], should therefore outperform designs that programme the base money itself. This is the least tested of the four, since the support is the BIS's own reasoning [12] and not behavioural evidence. Conjoint or field experiments that vary programmability and measure trust and usage would test it directly.

Proposition 4 (sovereignty-interoperability trade-off): The efficiency gains of more integrated cross-border models are inversely related to the monetary-sovereignty and capital-flow-management control retained by participants [25], so the willingness of central banks to join a platform should fall with the degree of integration it requires. The separation of multi-CBDC cooperation into distinct groups of participants after 2024 is consistent with this trade-off binding in practice. It is equally consistent with sanctions and geopolitical alignment, and the two explanations cannot be separated with the present

evidence. Comparing membership decisions across the three models of integration would help to discriminate between them.

Comparison with previous studies

We now set our results against earlier reviews and empirical work (Table 5). We take the scope of the earlier reviews from their own abstracts. Three are close to ours in design. Dionysopoulos et al. [22] offer a critical survey of the motivations for CBDC, its design options and its implications for monetary policy and financial stability. Ozili [23] reports from a systematic review a general consensus that a CBDC is a central bank liability with cash-like attributes, and notes that several studies caution against over-optimism because design cannot meet multiple competing goals. Bapat and Sharma [24] combine a bibliometric analysis of 371 Scopus articles covering 2012 to August 2024 with a qualitative review of 88 publications, and identify design and implementation (with technological and regulatory challenges), financial stability and monetary policy, and user perspectives as the main themes. We agree with these reviews on the main themes and on the caution about competing objectives. Our persistent tensions, such as privacy against AML/CFT and stability against usefulness, restate that caution in terms of observable design choices such as holding limits and remuneration. We differ in three ways. We treat the interaction between technology and regulation as the object of study and not as parallel themes. We separate retail from cross-border use. And we cover regulatory developments that fall after the search windows of these reviews, notably the 2025 United States prohibition and stablecoin framework, the redesign of the e-CNY and the euro-area legislative process. Earlier broad surveys point the same way. Auer et al. [13] describe questions on the cross-border dimension as unresolved, and our synthesis offers a partial answer for wholesale arrangements, namely that governance is the binding constraint, although this rests on a small number of projects. Kiff et al. [21] treat legal and regulatory considerations as integral to the decision to issue, as we do, but their aim is an operational framework for that decision, whereas ours is an explanation with testable propositions.

On adoption, our results agree with the individual-level literature on the importance of trust and privacy, but they differ on the strength of the signal. Solberg Söilen and Benhayoun [66] find, from 282 survey responses, that continued adoption of CBDC is highly probable and is fostered by expected performance, social recommendation and facilitating conditions, and that institutional efforts help only if households also trust the system. The live systems we reviewed show far lower take-up than such intentions suggest, which is consistent with an intention-behaviour gap. That reading is our interpretation of descriptive data. Tronnier and Qiu [34], who examine actual usage, are closer to the observed pattern in finding that privacy concerns reduce use. Xia et al. [67] report that privacy concerns about existing payment methods and task-technology fit raise willingness to use China's digital currency, that switching costs reduce it, and that relative advantage has no significant effect. The switching-cost result is consistent with our reading that entrenched incumbents limit retail take-up. The privacy result seems to point in a different direction from Tronnier and Qiu, but the two are compatible. Concern about the privacy of existing methods pushes users towards a CBDC, whereas concern about the privacy of the CBDC itself pushes them away, and the net effect depends on which concern dominates. Testing both concerns in one model is a natural next step.

On economic outcomes, the theoretical studies disagree. Brunnermeier and Niepelt [30] show that CBDC need not change allocations if CBDC-funded balances are passed back to banks, Keister and Sanches [40] show that it can crowd out deposits, and Andolfatto [64] and Chiu et al. [65] show that with bank market power an interest-bearing CBDC can raise deposit rates and lending. Our review does not resolve this disagreement,

because among the sources we selected none reports evidence from a live system on lending effects. What practice shows is that legislators and central banks act as if disintermediation risk were real, through holding limits [17, 56] and, in China, the redesign of the e-CNY [19]. This leaves unanswered Ozili's [23] call for empirical evidence on the effect of CBDC on the cost of credit and financial stability.

Table 5. Comparison of the findings with previous studies

Previous study	Scope or main result	Similarity with this review	Difference from this review
Dionysopoulos et al. [22]	Critical survey of motivations, design options, and monetary policy and financial stability implications	Same review type; shared focus on design and stability	We centre on the technology-regulation interaction, separate retail from cross-border use and add developments after 2023
Ozili [23]	Systematic review; caution that design cannot meet multiple competing goals; calls for evidence on credit, holding limits and country cases	Similar caution; holding-limit trade-off recurs in our tensions	We add evidence from live systems and the 2024 to 2026 regulatory trajectories; effects on credit remain unevidenced
Bapat and Sharma [24]	Bibliometric analysis of 371 Scopus articles to August 2024 and review of 88 publications; themes of design with technological and regulatory challenges, stability and policy, and user perspectives	Similar themes; both use Scopus	We treat technology and regulation as one interacting regime, separate use cases and search to October 2026
Auer et al. [13]	Guided tour of architecture, technology, privacy and macro implications; cross-border questions unresolved	Same attention to privacy and architecture	We give a partial answer on cross-border governance from wholesale projects; their review pre-dates 2024 to 2026 events
Kiff et al. [21]	IMF survey of retail CBDC with legal, governance and regulatory perspectives and an operational framework for deciding to issue	Legal and regulatory considerations treated as integral	Our aim is explanation and testable propositions, using outcomes from live systems
Solberg Söilen and Benhayoun [66]	Survey (n = 282): adoption highly probable, fostered by expected performance, social recommendation and facilitating conditions; trust needed	Trust conditions adoption	Stated intentions are more favourable than take-up in live systems
Xia et al. [67]	Survey on China's digital currency: privacy concern about existing methods and task-technology fit raise willingness; switching costs reduce it; relative advantage not significant	Switching costs fit the incumbent-competition reading	Privacy concern about existing methods raises willingness, whereas concern about CBDC privacy lowers use [34]; the two should be modelled together
[30, 40, 64, 65]	Theory on equivalence, crowding out and lending under bank market power	Practice reflects disintermediation concern through holding limits and the e-CNY redesign	No evidence from live systems on lending effects among the sources selected

The 2024-2026 regulatory turn and convergence towards tokenised deposits

The most important development of the review period is not a technological breakthrough but a convergence in policy design. China's decision to turn e-CNY wallet balances into interest-bearing commercial bank liabilities, the reliance of the United States on regulated stablecoins, and the BIS's unified-ledger agenda, in which tokenised commercial bank deposits settle against wholesale central bank money, all point in a similar direction: preserving the two-tier monetary system while modernising its infrastructure [12, 19]. The BIS's 2025 Annual Economic Report makes the same case against stablecoins, arguing that they fall short of the tests of singleness, elasticity and integrity that a tokenised unified ledger is better placed to meet [71]. This is an institutional position, and the BIS is a party to the debate. The euro area and the United Kingdom remain the principal jurisdictions still pursuing a cash-like retail CBDC, and they do so with explicit statutory safeguards. For theory, this suggests that the relevant object of study is shifting from retail CBDC as a new form of public money towards the configuration of public and private digital money on shared infrastructure.

Persistent tensions

Four tensions recur across the literature and define the design problem of public digital money. The first is privacy against AML/CFT, increasingly mediated by selective-disclosure cryptography [42, 46]. The second is programmability against monetary singleness [12]. The third is sovereignty against interoperability [14, 25]. The fourth is stability against usefulness, since the holding limits and non-remuneration that protect banks also reduce the attractiveness of the instrument to users [40, 58]. These tensions are not engineering defects to be eliminated but trade-offs to be governed.

Theoretical and policy implications

For theory, CBDC research should stop treating adoption as a single dependent variable. The weak retail adoption and the stronger cross-border functionality found in this review are not contradictory, because they reflect different constraint structures. Technology-acceptance and privacy theories suit retail CBDC, but they need to incorporate the incumbent payment ecosystem as a competing alternative, since intentions measured in isolation overstate the scope for switching [7, 19]. Institutional and international political-economy theories suit cross-border arrangements, where the unit of analysis is the coalition of central banks and not the individual user.

Four policy implications follow, including for emerging economies. First, where fast payment systems or mobile-money platforms already function well, retail CBDC should not be expected to drive financial inclusion on its own; the Indian and Chinese evidence shows how difficult it is to displace efficient incumbents [19, 61]. Second, the returns to wholesale and cross-border interoperability are more demonstrable, which makes a wholesale-first sequence such as that in Indonesia's Project Garuda a defensible hypothesis [62, 63]. It remains a hypothesis, because no wholesale-first path has yet produced evidence on inclusion or stability outcomes. Third, privacy guarantees and stability safeguards are best written into enabling legislation, because statutory commitments are what build the soft trust that drives adoption [33, 59]. Fourth, regulated stablecoins and tokenised deposits should be treated as part of the same policy space as CBDC and not as external threats, since the design of each shapes the demand for the others.

Research agenda

Table 6 sets out a research agenda derived from the gaps identified in the synthesis. Three priorities stand out. The first is causal evidence on adoption: the field relies heavily on cross-sectional surveys of intentions, while live systems now offer opportunities for quasi-experimental designs around programme changes such as programmable benefit transfers in India or the move to interest-bearing balances in China. The second is the valuation of privacy technology: whether verifiable cryptographic guarantees change behaviour, or whether statutory guarantees are what users actually respond to. The third is comparative institutional analysis of cross-border governance after the separation of multi-CBDC cooperation into distinct groups of participants.

Table 6. Future research agenda

Theme	Research question	Suggested design
Causal adoption	What design or policy changes actually move retail CBDC usage?	Quasi-experiments around programme changes (e-CNY interest, e-rupee programmable transfers)
Privacy valuation	Do users respond to verifiable cryptographic guarantees, statutory guarantees, or both?	Choice experiments; field experiments
Programmability	At what point does programmability shift from adding value to eroding trust?	Conjoint analysis; behavioural experiments
Cross-border governance	How do the governance models of mBridge and Agorá affect participation and volumes?	Comparative institutional case studies
CBDC and stablecoins	How do stablecoin regimes and CBDC designs jointly shape currency competition?	Structural models; cross-country panel data
Quantum readiness	What is the frontier among privacy, security and performance for quantum-safe CBDC at scale?	Engineering benchmarks; prototype evaluation
Sequencing in emerging economies	Does a wholesale-first path outperform retail-first paths on inclusion and stability?	Comparative case studies (for example Indonesia, Nigeria, India)

Limitations

This review has four limitations. First, the field is moving quickly, and several 2025 and 2026 developments rest on institutional documents and policy analysis that have not yet been evaluated in peer-reviewed work; we identify these in the text, and some, such as the decision on the digital pound, may have changed after our search date. Second, as a critical review it relies on purposive and not exhaustive selection of sources, so relevant studies may have been omitted, although the Scopus map situates the selected sources within the wider literature. The search also relied on a single bibliographic database and on English-language sources, so studies indexed only in Web of Science or in regional databases, including Chinese-language scholarship on the e-CNY, may be under-represented. Third, central banks and the BIS are simultaneously actors in, and major producers of evidence on, CBDC, so institutional perspectives may be over-represented despite comparison with independent studies. Fourth, the keyword classification is approximate and, as shown above, cannot by itself measure integration between technology and regulation, and individual-level adoption evidence is dominated by intention-based surveys, which limits causal inference.

CONCLUSION

This review set out to examine how advanced cryptographic solutions and hybrid blockchain architectures interact with evolving regulatory frameworks to shape the economic outcomes and user adoption of CBDC, and how that interaction differs between retail and cross-border implementations. The evidence supports three answers. First, technology and regulation co-evolve. Privacy-enhancing cryptography and two-tier or unified-ledger architectures are engineered to satisfy specific regulatory constraints, and regulation in turn selects among designs, as the redesign of the e-CNY shows. Second, the interaction differs by use case. In retail settings, trust, privacy and competition from efficient incumbents, and not cryptography, appear to govern adoption, and some major jurisdictions have chosen prohibition or deliberately limited designs. In cross-border and wholesale settings the technology delivers its clearest value, but governance, sovereignty and geopolitics set its limits. Third, economic outcomes depend on how regulation contains disintermediation risk, through holding limits and remuneration rules, at some cost to the usefulness of the instrument. These answers are consistent with the four propositions, which we offer as hypotheses to be tested and not as established findings. Future scholarship should theorise the two use cases separately and study them together with the parallel rise of regulated stablecoins and tokenised deposits.

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