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Central bank digital currencies: A critical review

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ABSTRACT

This critical literature survey offers a comprehensive understanding of the key aspects and implications of central bank digital currencies (CBDCs) as a rapidly evolving area of academic and policy research. We review in depth the key discussion around motivations for the introduction of CBDCs and their design (looking at options of availability, provision, access, and supporting infrastructure). In addition, we review studies and arguments laid out on the implications that the introduction of CBDC may have for monetary policy and financial stability. Finally, we identify sub-areas of CBDC research that need further investigation in future research.

1. Introduction

The evolution of monetary systems has often been viewed as a private-sector development (Clower, 1967; Kiyotaki & Wright, 1989, 1993; Menger, 1892), however, the most significant and consequential shifts have been instigated by state responses to extraordinary events (Goodhart, 1998). Throughout history, states have encouraged the development of monetary systems in order to support their geopolitical and economic expansion (such as in the cases of the Macedonian Engels, 1980; Graeber, 2014 and British Ingham, 2004 empires); and the development of central banking and finance to accelerate and sustain the capitalistic system (Varoufakis, 2013). Furthermore, large economic and political shocks like the Great Depression of 1929–39 and the two World Wars (1914–18 and 1939–45) have triggered modifications to the gold standard monetary system[1] (Eichengreen & Flandreau, 2005).

Likewise, in the most recent times high competition amongst financial players, global upheavals such as the Global Financial Crisis of 2007–09, and, in the past three years, the COVID19 pandemic and Russian–Ukrainian conflict in Easter Europe, have intensified the demand for more adaptable monetary and fiscal policies that address contemporary needs while simultaneously mitigating emerging challenges for the financial system. Those chiefly include increasing digitisation, declining cash usage, ineffectiveness of monetary policy, and widening social divisions in the backdrop of proprietary financial solutions, such as fintech and cryptocurrencies, which threaten national economic sovereignty.[2] Moreover, as the digital economy becomes increasingly important and reliant on privately owned digital platforms with proprietary and opaque rules – potentially expanding into all-encompassing metaverses – central banks are preparing for another intervention of epochal proportions.

Central bank (CB) Digital Currencies, or CBDCs, are a novel form of digital central bank (CB) money that represent the culmination of state efforts to manage this digital transition. They are designed to provide attractive instruments for both wholesale and retail functions, as well as bolster CBs' influence and control over the economy through new monetary, fiscal policy tools and programmable capabilities. As with past shifts in monetary policy, their introduction may have significant disintermediating effects on the financial system, such as disintermediating commercial banks and some of the operation of private money providers. While 86% of CBs are involved in CBDC research, 60% in experiments and 14% in live pilot deployments (BIS, 2021), independent academic research into this topic is still nascent; thus a comprehensive understanding of their key aspects and implications remains limited.

Given the intricate nature of the CBDC topic, it is imperative for a review to critically evaluate the existing body of literature and not just "organise" it. That is to provide a solid foundation for the ongoing

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[1] The Great Depression resulted in countries abandoning the gold standard in favour of more flexible exchange rate systems. The standard was further disrupted through various forms of government intervention necessary to finance war efforts during the two World Wars. The gold standard became defunct following World War II as governments adopted new monetary policies such as fixed or floating exchange rates.

[2] As outlined in Section 3.

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CBDC debate, highlight the aspects that remain relevant and articulate why some aspects of the debate may now be obsolete. The critical approach we follow also helps to identify emerging research pathways and facilitate future research avenues in this domain.

In addition to be critical, this review also takes an interdisciplinary approach, encompassing finance, economics, and computer science. This approach considers macroeconomic and regulatory aspects, both of which have significantly influenced the CBDC discussions, as well as it connects the CBDC developments to the dynamics of the cryptocurrency space.

Previous reviews, particularly those developed by CBs,[3] as well as Kiff et al. (2020) primarily present summaries of studies and exploratory experiments, and/or adopt a non-multi-disciplinary approach.

Moreover, the studies of Hoang et al. (2023), Nobanee et al. (2022) and Tronnier et al. (2020) utilise a systematic method to categorise existing research on CBDCs but do not evaluate it critically. Overall, existing literature reviews are exploratory and overlook the critical element while also often not accounting for the broader multi-disciplinary body of work, thus missing the bigger picture.

In contrast, our work presents a critical, comprehensive, and multidisciplinary examination of the literature, a perspective currently absent in CBDC literature. Through this, we provide a robust foundation for the material aspects of the CBDC debate and illuminate emerging research avenues.

To this end, we organise our discussion into five distinct segments. Section 2 critically examines key concerns regarding the definition and categorisation of CBDCs before providing a universal description. Section 3 delineates arguments for CBDC issuance to further elucidate the need for their introduction and to pave the way for the subsequent discussion on their design. Section 4 explores the CBDC design space and options. Section 5 addresses key monetary and macroprudential considerations. Finally, Section 6 details arguments against CBDC issuance.

These sections are interconnected and vital in achieving a critical examination and robust foundation for the debate and the emerging research on CBDC. In fact, they critically examine what CBDCs can be and can achieve, why we may need them, how we can design them and then – depending on the design choices – what the main implications and the arguments in favour and against adopting them are.

In Section 2, we provide a more flexible and universal definition than the definitions provided in the extant literature reviews. Our definition is a result of a critical scrutiny of the CBDC literature and seeks to include all possible variations of CBDCs, by anchoring them to our contemporary understanding of traditional money and more innovative digital monies. We particularly emphasise the difference between centralised CBDC and decentralised cryptocurrencies, the most prominent ones being Bitcoin and Ethereum, and pinpoint also potential weaknesses in the typical money-categorisation.

We then elucidate the need for CBDCs and outline the primary motivations behind their introduction in Section 3. To the best of our knowledge, we are the first to clearly relate the CBDC developments with specific events transpiring in the economy. This requires a critical review of a substantial corpus of literature, primarily the one developed by Central Banks around the world.

The debate surrounding the potential usefulness of CBDCs also sets the stage for a discussion on their possible designs, which are examined in Section 4. Using an interdisciplinary approach, we draw insights from computer science and the literature focusing on financial stability and monetary policy to critically assess drivers and implications of each design choice. These insights are then further expanded in Section 5.

Considering the discussion developed in the earlier sections around the CBDC definition and design, and its monetary and financial implications, Section 6 concludes the review by evaluating whether CBDCs are apt tools for achieving their proposed goals. In this context, we critically assess a subset of 'contrarian' literature not much highlighted in any of the referenced reviews.

2. Defining CBDCs

Most literature defines CBDCs narrowly, for instance, many CBs focus on their retail and consumer-facing aspects, as outlined in a joint report by seven central banks[4] and the BIS in which CBDCs are defined as "a digital payment instrument, denominated in the national unit of account, that is a direct liability of the CB" (Group of Central Banks, 2020). This notion is echoed in individual reports such as those from the Bank of England (BoE), Bank of Canada (BoC), European CB (ECB), which respectively define CBDCs as "an electronic form of CB money that could be used by households and businesses to make payments and store value" (BoE, 2020), "a digital form of CB money that can be used for retail payments" (Chiu et al., 2019), and "a CB liability offered in digital form for use by citizens and businesses for their retail payments" (ECB, 2020). Some other reports emphasise its advantageous role in facilitating the execution and settlement of cross-border transactions between financial institutions, therefore defining CBDCs as a strictly wholesale instrument (Group of Central Banks, 2018, 2020).

Such distinctions are not limited to a CBDCs retail or wholesale functionality. A distinction can also be made between a type of CBDC that is different from CB reserves and another that pertains to the expansion of the reserve system to the wider private sector. Indicatively the Committee on Payments and Market Infrastructures (CPMI, 2018) define CBDCs as "a digital form of CB money that is different from balances in traditional reserve or settlement accounts", a notion that is echoed in others such as Barrdear and Kumhof (2016), Griffoli et al. (2018), and Kumhof and Noone (2021) that envisage a remunerated or interest-bearing CBDC, distinct from existing traditional reserves. Kumhof and Noone (2021), also explicitly mention that "CBDC and reserves are distinct, and not convertible into each other", and Griffoli et al. (2018) that CBDCs would "differ from other forms of money typically issued by central banks: cash and reserve balances". On the other hand, Meaning et al. (2018) define CBDC as "any electronic, fiat liability of a CB that can be used to settle payments, or as a store of value" noting that CBDC "already exists in the form of CB reserves". Overall, narrow CBDC definitions reflect the experimental state of research.

In this thematic survey of CBDC research, we start by providing a more and universal definition of CDBCs that can include and encompass the variety of definitions retrieved in the reviewed literature. Similarly to Kiff et al. (2020) we define CBDC as a digital liability of a CB, or other competent authority, representing a jurisdiction's sovereign currency available to the private sector. In contrast to others, this abstractive definition accommodates the full range of CBDC possibilities. While a dominant CBDC design may eventually emerge, a more broad definition would still be preferable as different jurisdictions will adopt different CBDC options to accommodate their diverse needs and legal frameworks (BIS, 2021). A CBDC is distinct from other monies in a number of ways.

The Committee on Payments and Market Infrastructures (CPMI, 2015) was the first to consider CBDCs in the context of different types of

[3] See: BoE (2020), Carapella and Flemming (2020), ECB (2020), Fung and Halaburda (2016), Griffoli et al. (2018), Group of Central Banks (2018, 2020), Kahn et al. (2019) and Meaning et al. (2018) from the International Monetary Fund, the Committee on Payments and Market Infrastructures (Bordo & Levin, 2017; CPMI, 2018) from the National Bureau of Economic Research, and Bech and Garratt (2017) from the Bank of International Settlements (BIS).

[4] The Bank of Canada, European Central Bank, Bank of Japan, Sveriges Riksbank (Central Bank of Sweden), Swiss National Bank, Bank of England, and the Board of Governors Federal Reserve Systems.

Table 1
Money classification.

Feature	Deposits	eMoney	Crypto	P. Metals	Cash	Reserves	CBDC
Medium of exchange	✓	✓	✗	✗	✓	✗	✓
Store of value	✗	✗	✗	✓	✗	✓	?
Unit of account	✓	✓	✗	✗	✓	✗	✓
Status	D	D	D	P	P	D	D
Convertibility	✓	?	✗	✗	N/A	✓	?
Issuer	CM	PS	N/A, PS	N/A	CB	CB	CB
Access	A	A	T, A	T	T	A	T, A
Availability	R	W, R, U	W, R, U	W, R, U	W, R, U	W	W, R, U

Deposits: Funds held an account at a commercial bank by a customer.
eMoney: A digital currency stored electronically and issued by a private sector entity.
Cryptocurrency: A digital form of money upended by a decentralised network utilising cryptography.
P. Metals: Naturally occurring metals, such as gold or silver, that have an economic value.
Cash: Physical currency. Reserves: Money held at central banks Status, P: Physical, D: Digital.
Issuer, CB: Central Bank, CM: Commercial bank, PS: Private sector.
Access, A: Account T: Token.
Availability, W: Wholesale, R: Retail, U: Universal.

money by examining the physical or digital state of money tokens, and whether their exchange can occur in a peer-to-peer manner, or requires a financial intermediary. Similarly Bech and Garratt (2017) introduce their "money flower" model which distinguishes between accessibility, digital or physical state, issuer and "exchange mechanism". Bjerg (2017) distinguishes between reserves, cash, and commercial bank money based on parameters such as the issuer, physical or digital state and wholesale or retail availability. Adrian and Mancini-Griffoli (2019) propose a "money tree" that classifies B-money, meaning fiat backed money issued by private actors, eMoney, and I-Money, meaning commodity-backed eMoney according to "type" (token/account, explored further in 4.3), "value" (convertibility at par/penalties applied), "backstop" (entity where liability originates) and technology (database versus DLT/blockchain, a form of decentralised record keeping explored in 4.4). Finally, BoE (2020) consider the functions of money and their convertibility in their money classification. The frameworks are summarised in Table 1, were we also consider the wholesale, retail, and universal availability of money. By wholesale availability we mean money intended for use by appointed (financial) entities usually for interbank transactions. By retail money, we mean money intended for use by the wider domestic private sector as a medium of exchange. Universal money is also available to foreign entities.

Naturally, such categorisations are imperfect. In practice, some households and individuals use deposits and cash as store of value, despite high rates of inflation. Similarly, proponents of certain cryptocurrencies would argue that they can serve as a medium of exchange, store of value or both. Indicatively, such arguments can be made in the case of Bitcoin which was explicitly devised as a medium of exchange, or "peer-to-peer electronic cash" (Nakamoto, 2009), and is even formally recognised as legal tender in countries such as El Salvador and the Central African Republic (Savage et al., 2022).[5] Additionally, its diminishing rate of inflation and fixed maximum supply support the narrative of bitcoin as "digital goal", "sound money", or "inflation hedge", and ultimately, store of value.[6] Ethereum's ether (ETH), the second most popular cryptocurrency, has been used as a unit of account for many online non-fungible token (NFT) marketplaces. In practice however, cryptocurrencies are, neither good mediums of exchange, nor good stores of value or units of account; their adoption for retail payments remains low (Jonker, 2018), roll out as legal tender problematic (Morris, 2022), and high correlation with other financial assets does not offer hedging benefits (Klein et al., 2018). Moreover, in the case of ether, its use as a unit of account can be attributed to excitement, the relatively niche and self-referential culture of the NFT space, and the extreme market price volatility of NFTs, making accurate price quotes unnecessary. There is also a lot of variation in each category. For instance, cash and deposits can serve as better or worse stores of value depending on domestic inflation rates, and, if stablecoins[7] are to be considered under cryptocurrencies, those could better serve as mediums of exchange and units of account, due to their relative stability.

Finally, it is worth noting that sufficiently decentralised cryptocurrencies, such as Bitcoin and Ethereum, stand in contrast with CBDCs. "Decentralisation" refers to the extent of distribution of authority and control across a network; so, a higher degree of decentralisation indicates a greater dispersion of control. We elaborate on this argument in Section 4, but the primary points are crucial here for an understanding of CBDCs. Decentralised cryptocurrencies rely on open blockchains, co-governance, and, in some instances, token schemes. For cryptocurrencies, there is still a trade-off between level of scalability and the degree of decentralisation. A limitation to scalability would likely be unacceptable for CBDCs as they are intended the whole economy and even enhance financial inclusion. In addition, decentralisation might also be an entirely undesirable feature in cases where the CBDC projects are intended to improve programmability and control of money by Central Banks in contemporary monetary systems. For these reasons, the material interconnectedness between digital decentralised and centralised currencies is quite low given they have different purposes and often of interest to different parties.

3. Motivations for issuing CBDCs

3.1. The three phases of development

Regarding arguments supporting CBDC issuance, we observe that these are informed and prompted by concurrent macro-economic events and changing trends in the financial system. Three main developmental stages can be identified: (*i*) For much of the decade following the 2008 financial crisis, many CBs had to contend with persistently low inflation levels; as such, CBDCs were proposed as a potential remedy. (*ii*)

[5] In fact competing narratives around Bitcoin have even resulted in hard forks (non-backwards compatible changes) of the protocol, such as Bitcoin Cash.

[6] Even Bitcoin's proponents are divided as to which function it should serve, resulting in incompatible variations of the protocol. Bitcoin (BTC) and Bitcoin Cash (BCH) are such example.

[7] Stablecoins are cryptocurrencies designed to maintain a more stable market price, by usually tracking the value of a national currency such as the USD. They are explored further in Section 3.1.3.

The emergence of fintech, cryptocurrencies and blockchain technology prompted discussions regarding a structural reform of the financial system to achieve greater efficiency, cost-savings, transparency and novel features. (*iii*) More recently, the proliferation of foreign and private money solutions has been seen as a threat to financial sovereignty leading to CBDCs being promoted as a possible response. In addition to these reactive developments, many sophisticated arguments have been put forward that did not directly relate to then current economic events. Examples include using CBDCs to address declining cash usage, preserving access to CB money in an increasingly digitised world and facilitating financial inclusion for all citizens. In the following sections, we will explore both types of arguments in more detail.

3.1.1. The backdrop of persistent low inflation

Following the 2008 financial crisis, stimulating efforts such as quantitative easing (QE) proved less effective than initially anticipated, leading to an increase in the size of the financial market and meager growth in the real economy (Simmons et al., 2021). In the backdrop of persisting low inflation, proposals for unconventional monetary policy utilising government electronic money emerged. Indicatively Agarwal and Kimball (2015), Dyson and Hodgson (2016), and Rogoff (2016) suggested that "digital cash"[8] could eliminate the zero lower bound. By charging negative interest rates (demurrage fee) on government electronic money, CBs would encourage spending and stimulate the economy. Naturally, households and firms would be incentivised to switch the demurrage-charged digital cash for other forms of money, so limits on convertibility, or the elimination of physical cash altogether would also be necessary. At the same time Agarwal and Kimball (2015) and Dyson and Hodgson (2016) in particular, have recognised the fiscal utility of digital cash, especially through the provision of "helicopter money",[9] a benefit also recognised by the Group of Central Banks (2020), especially for identified users. Indicatively, Agarwal and Kimball (2015) suggest that by paying a high interest on CBDC, CBs can simultaneously stimulate the economy and increase the supply of money by instead increasing the value of an interest-bearing CBDC relative to other monies. This use of government electronic money for new monetary and fiscal policy techniques remained staple in CBDC literature since. Hence the first stage in the CBDC evolution was motivated by the need for expanding the monetary and fiscal policy toolbox.

3.1.2. CBDC and improvements in payment systems

During the mid 2010s blockchain hype which peaked in 2017–2018, the enterprise sector explored the potential of blockchain for cost savings and increased efficiency through ledger co-maintenance, programmability and disintermediation; however these ambitions were not fully realised due to a range of factors including consensus overhead costs, technological complexity implementation requirements, lack of suitability or need for firm control over infrastructure (Bousquette, 2022; Disparte, 2019; Gartner, 2019).

This brief exploration, however, influenced discussions on CBDC design choices and in particular the use of alternative technologies for CBDC infrastructure as a source of efficiency, cost effectiveness, interoperability and novel features. Bech and Garratt (2017) and Raskin and Yermack (2016), but also later CPMI (2018), Griffoli et al. (2018), and Kahn et al. (2019), identify of distributed ledger technology (DLT)/blockchain[10] and cryptographically secured tokens as alternative ledger and access methods for money. The authors discuss the trade offs from the perspective of the CB, the financial system and in particular commercial banks, and the end-consumer perspective but do not arrive at conclusive evidence as to what options are ultimately the best. Auer and Boehme (2020) summarise the main points of this debate and connect it to contemporary consumer needs.

Yet, as in the case of industrial applications, concurrent practical experiments suggested that blockchains might not be a good substitute for conventional databases owning to the overheads of consensus mechanisms (indicatively Chapman et al., 2017 and Chiu & Koeppl, 2017) and that the debate between tokens and accounts as access methods was ultimately immaterial due to reporting requirements and the nature of digital transactions that necessarily produce identifiable "fingerprints" (Claussen et al., 2021).

However, as outlined by BIS (2021), the notion of utilising CBDCs as a potential source of efficiencies was not abandoned, but re-framed under more pragmatic terms. Barrdear and Kumhof (2016) suggest that an CBDCs could result in substantial efficiency gains by avoiding withdrawal and processing fees, a claim also echoed in He et al. (2017). Andolfatto (2021), Chiu and Wong (2021), and Keister and Sanches (2021) outline CBDC efficiency benefits in payment systems whereas Auer et al. (2022) the potential benefits for cross-border transfers. Group of Central Banks (2020) also suggest that CBDCs can provide a common method of transfer between proprietary payment systems, making transactions cheaper and more efficient. This additional payment system can also enhance the resilience in payments according to the BoE (2020). The same report outlines that the benefits of efficiency and robustness can be brought to cross-border payments, although as Auer and Boehme (2020) highlight, such matters are subject to political considerations. Finally, World Bank (2021) outlines how CBDCs could facilitate interoperability and standardisation in cross-border transactions remedying existing frictions such as lengthy transaction delays costs (due to intermediation), lack of traceability and transparency, hindering anti-money laundering (AML) and counter-terrorist financing (CFT) checks. This exploration reinforces the notion that the novelty and impact of CBDCs relies chiefly on political and procedural consideration and the potential expansion of the role of the CB.

3.1.3. The stablecoin and foreign CBDC threat to financial stability and sovereignty

This second exploratory phase was succeeded by concerns stemming from the rising competition from private and foreign money.

Decentralised stablecoins are a type of cryptocurrency that seeks to mitigate volatility by maintaining a stable price against a predetermined target. This target can be a financial asset, real asset, other cryptocurrency, or a combination thereof, but is most often the US dollar, due to its status as a global reserve currency and its stability. Stablecoins are important for several reasons, including reducing volatility in the cryptocurrency market, enabling crypto-holders to maintain liquidity, providing a blockchain-native unit of account, and enabling much of the functionality of decentralised finance (DeFi) protocols.[11] Additionally, they retain some of the desirable characteristics of non-stablecoin cryptocurrencies, such as censorship resistance, borderless operation, and decentralised issuance and access. Owing to this utility, their use[12] has increased over the past years.

Yet, stablecoins were also perceived by regulators as a potential threat to financial stability, even more so than cryptocurrencies, owing to their positioning as payment instruments. In many cases, they utilise

[8] The term CBDC was only popularised in a 2018 report of the same name by CPMI (2018).

[9] A form of fiscal policy where a central bank creates new money and distributes it directly to the public, typically through government spending, in order to stimulate the economy.

[10] Blockchains are type of DLT with specific features. In their analysis, CBs, utilise the term DLT to distance their offering from cryptocurrencies. Blockchain and DLT are analysed further in Section 4.4. For the purposes of the present we will use the terms interchangeably.

[11] DeFi applications blockchain-based and decentralised alternatives to traditional financial applications, such as borrowing, lending, derivatives, and insurance.

[12] The total stablecoin market capitalisation reached a peak of approximately $200 billion in April of 2022 according to defillama.com.

unproven stability mechanisms which often fail[13] negatively affecting (i) financial entities with stablecoin exposure, (ii) individual investors and financial markets, (iii) investor confidence in cryptocurrencies, and (iv) their use as payment instruments, according to the Financial Stability Board (FSB, 2022). The G7 has expressed additional concerns which include issues with stablecoin governance, cyber risks, market integrity and pricing, tax compliance, as well as data, consumer and investor protection. For stablecoins that achieve global scale, they also cite potential concerns for financial stability (similar to those of the FSB), and the implementation and efficacy of monetary policy (G7, 2019). Moreover, due to the market dominance of certain stablecoins, such as Tether's USDT, their potential failure has also been perceived as a potential systemic risk for the financial system, and for the financial sector exposed in such assets, leading to direct regulatory intervention (Browne, 2021). Due to their substitutability with stablecoins, the introduction of CBDC was seen as a way to mitigate the negative effects described above.

Despite their popularity, stablecoins fall short as a means of payment due to throughput limitations of blockchain, transaction costs, and redemption limitations (Adachi et al., 2022). Moreover an argument can be made that they lack the institutional backing to facilitate adoption and integration with existing payment systems and procedures. Those issues were to be mitigated by global private stablecoins. Global private stablecoins were an attempt by established big tech and big finance players to capture parts of the monetary system by leveraging their dominant position. Perhaps the most popular was Facebook's (now Meta) Libra (later Diem). Diem was a "blockchain-backed"[14] financial network that aimed to enable "open, instant, and low-cost movement of money" and universal access to related financial services. While its economic design became notably less ambitious owing to regulatory pressure, at one point Diem was to be backed by a "basket" of currencies, financial and real assets creating a private "super-currency"[15] to be used across the platforms of Meta and its partners (Amsden et al., 2020). Putting things into perspective, if each of Facebook's active monthly users held 3 units of Diem, then it would become more widely used than the United States Dollar.[16] In the prospect of Diem's destabilisation of the global financial system and hindrance of CB influence on monetary policy (Diez de los Rios & Zhu, 2020), regulatory response was stern (Zetzsche et al., 2019) leading to the scaling down and ultimately abandonment of Diem (Levey, 2022) and of other similar efforts.[17]

In parallel to Meta's announcement of Diem, China became the first major economy to successfully test CBDCs on a large scale (Areddy, 2021). Earlier, the Bahamas had become the first country to launch a CBDC, the Sand Dollar, followed by Nigeria's eNaira, and Jamaica's JAM-DEX. Concurrently, Saudi Arabia, the United Arab Emirates, Canada, France, Singapore, Tunisia, and the Eastern Caribbean Economic and Currency Union launched pilot CBDCs.[18] CBDCs research was also expanding virtually everywhere (BIS, 2021), leading to concerns about financial sovereignty.

In particular, Yeyati (2021) highlights the prospect of digital dollarisation stemming from potential easy access to foreign CBDCs, and counter-propose a domestic CBDC issuance to mitigate it. Andolfatto (2021) expands this argument by suggesting that a domestic CBDC would reduce consumer incentives to adopt foreign and private monies and thus safeguard financial sovereignty, by ensuring that the national currency continues to be perceived as financially secure, and competitive in terms of features. Besides safeguarding against foreign CBDCs and private moneys, Ferrari Minesso et al. (2022) offer an additional explanation for the fast pace of CBDC development. They suggest that potential imbalances in the international monetary system stemming from a lack of monetary policy autonomy as a result of CBDC introduction explain why issuing a CBDC quickly could provide a significant competitive edge. Yet (Chorzempa, 2021) notes that such advantage might be short lived due to changes in technology and markets.

Competing monies pose additional concerns that a CBDC can protect against. As highlighted by BoE (2019, 2020) and CPMI (2018) those may neither offer the same level of safety and confidence as existing payment systems nor be subject to the same protections and guarantees as deposits or cash. Additionally, CBDCs can counteract the potential for private payment systems to become natural monopolies, thereby reducing market dominance and concentration risk (Group of Central Banks, 2020; Kiff et al., 2020). On the contrary, a "well-designed" CBDC can facilitate healthy competition between private payment service providers (BoE, 2020). Finally, CBDCs can mitigate the impact of exclusions and bans from global financial systems and standards such as SWIFT, as was recently the case with Russia (BBC, 2022).

3.2. Additional sophisticated arguments for CBDC issuance

3.2.1. Declining use of cash and financial inclusion

Surveys in Canada (Henry et al., 2018), the United States (Foster & Greene, 2021), Europe (ECB, 2022), the UK (BoE, 2022), and in particular Sweden (Sveriges Riksbank, 2018), demonstrate a diminishing usage of cash, in comparison to other forms of payment owing to a collection of factors which include shifting consumer preferences, increasing digitisation, and the knock on effects of COVID-19. This has two important implications. First, absent a CBDC and by choosing not to use cash, consumers no longer have access to the CB balance sheet and have to instead rely completely on the private sector money. Second, if cash is gradually phased out, financial inclusion will be impacted significantly (CPMI, 2018). Commercial banks and other financial intermediaries that provide the main substitute for cash, i.e., deposits and eMoney, are incentivised, as for-profit institutions, to only extend their services to countries, communities, or individuals if they can generate a profit. This could leave underprivileged groups at risk, particularly in countries with underdeveloped financial systems and low financial penetration where commercial banks may be financially constrained. This presents a compelling case for a CBDC to serve as a medium of exchange and store of value to combat financial exclusion (BIS, 2021; Bordo & Levin, 2017; Camera, 2017; Group of Central Banks, 2020). Additionally, CBDCs can also help CBs recoup seigniorage revenue lost from the declining cash usage (Kahn et al., 2019).

3.2.2. Privacy in payments

Despite its declining usage, cash remains an important instrument for preserving privacy in payments due to its anonymous nature (Kahn & Roberds, 2009). If cash use diminishes, or it is discontinued in favour of alternative public or private solutions, consumers will demand a private alternative. In fact, research suggests that this is one of the driving rational for CBDCs (ECB, 2021). The lack of privacy in payments can hinder consumer welfare, for instance, Garratt and Lee (2022) demonstrate that payment data collection techniques from private actors can contribute to the establishment of monopolies. Here the role of the CB as the CBDC issuer is particularly important, since it can, as a not-for-profit organisation, commit to the non-exploitation of user data for commercial purposes.

Gross et al. (2021) showcase how CBDCs with cash-like privacy can be achieved through zero-knowledge proofs, whereas BoE (2020) and Claussen et al. (2021) deem the possibility of entirely anonymous

[13] A recent example was that of UST (Dionysopoulos, 2022).

[14] It is unclear whether Diem's infrastructure would be classified as a blockchain, or whether the term was used to benefit from the publicity surrounding decentralised blockchains.

[15] A currency used globally and backed by a basket of reserve currencies and assets.

[16] Author's calculations based on Facebook monthly users from Meta Q3 2022 Earnings Slides, page 14 (Meta, 2022) and Claims in U.S. dollars, in December 2022 from COFER (data.imf.org).

[17] JPM Coin by JP Morgan was another such attempt.

[18] More information available at cbdctracker.org.

or private CBDCs unlikely, citing that digital transactions produce "digital fingerprints" that, given enough time and resources, can be traced back to parties involved in the transaction, among other regulatory and political considerations. In practice, complete anonymity is hard to achieve even in cases where a payment instrument is specifically devised with anonymity in mind and utilises state of the art techniques (CipherTrace, 2021). The overarching consensus is that some level of privacy, and not anonymity from the CBDC operator, can be achieved, thus providing consumers with an alternative to private sector payments solutions that can be privacy-invasive (Bech & Garratt, 2017; Erlandsson & Guibourg, 2018; Group of Central Banks, 2020). The concept of "tiered privacy" is also explored, with larger transactions revealing more information about the transacting parties. As anonymity from the CBDC operator is unlikely, two additional benefits of CBDC become apparent. Firstly, with sufficient adoption, CBDCs could positively contribute to limiting or eliminating black markets that rely on cash. Secondly, as a result of this, they could also lead to an increase in tax revenues and a reduction in tax evasion, in particular from the adoption of eMoney by tax evaders or criminals (McAndrews, 2020).

The debate on CBDC privacy and anonymity is still-unfolding with significant implications in a number of areas. Indicatively, Bordo and Levin (2017) and Rogoff (2015, 2016) argue that the widespread use of CBDC, or its introduction as a replacement for cash could also reduce criminal activity, whereas Wang (2020) shows that a CBDC with cash-like privacy could increase tax evasion. Finally, it should be noted that due to the centralised nature of the operator and digital-record keeping a CBDC can be used as a tool for mass surveillance, something that many CBs are considering and actively designing against (Fanti et al., 2022; Uberti, 2022), although this could be perceived as a desirable property in certain regimes.

3.2.3. Programmability of payments and money

Another argument in favour of CBDC issuance is their facilitating of programmability of money and payments. Programmability in money refers to programmable functions at the unit level, allowing (or disallowing) their use or altering their value based on predetermined rules.[19] Programmability of payments is an adjacent concept that refers to payment executions based on predefined conditions. The BoE (2020) recognises three possible approaches to CBDC programmability, namely (*i*) integrating the functionality into the fundamental ledger, (*ii*) providing the capability through an additional "module", (*iii*) or "outsourcing" it to PSPs. Each option presents different trade offs. For instance, implementing native programmability to a CBDC would potentially hinder throughput, as more computations would be performed as part of the payment execution, but presents the safest option as it does not rely on third parties that have a higher chance of being compromised than the CB.

Non-native programmability on the other hand presents trade offs that resemble those of the "oracle problem" in blockchains. Blockchains are entirely isolated from the outside world and are unable to natively access data such as a node's hardware, file system, or other information feeding through the internet. As a result, for processing real-life data necessary for some of their functions (for instance, the time, date, or market prices) they rely on smart contracts called "oracles" which "feed" (and some times pre-process to save computational resources) real-world information to blockchains. While this increases the functionality and throughput, it comes with the risk of compromised or inaccurate data sourcing. Programmable CBDCs relying on external modules or payment service providers (PSPs) for their functionality will face a similar trade off and need to trust that those sources are reliable and necessarily compromise on some decentralisation and potentially even security.

[19] This would break the fungibility of money, especially if tied to identity.

To summarise, 1 shows that CBs have three distinct options when it comes to programmable CBDCs. In Model 1 they can achieve programmability and high throughput by sacrificing security, in Model 2, they can achieve programmability and security by sacrificing throughput, whereas in Model 3 they can abandon the prospect of programmability to maintain security and high transaction throughput. This trilemma is presented in figure.

Nonetheless programmability in payments and money has significant implications. At a basic payment-level it can facilitate automated money transfers, for salary, subscription, or other purposes, based on predetermined rules. It can also bolster the implementation of other policies such as special taxes or discounts that can be applied when a unit is spent on a transaction that meets certain criteria. For instance, money spent on carbon intensive activities could be valued differently (lower) than money spent on education (valued higher). This can also influence the implementation of fiscal policy by mitigating moral hazard. For example, programmable money could disallow the spending of stimulus checks or other benefits on certain products, such as alcohol or tobacco, or even encourage its spending on essential goods (through adjusting its value at the point of sale).

At this point, it is worth noting that programmability at the unit of money is not always desirable. The ECB has announced that such feature "is not in line with the guiding principles of the digital euro endorsed by the Governing Council" (Digital Euro Project Team, 2022). The political economy implications of the above are very large and would need careful consideration.

4. CBDC design space and options

In this section, we review the current debate surrounding the design of CBDCs by looking at five main aspects: (*i*) its nature as a CB liability (in terms of expanding the existing reserve system or creating a new form of CB liability); (*ii*) its availability to end-users (whether wholesale, retail, or universal digital currency); (*iii*) its provision through a direct, indirect, or hybrid system depending on the level of involvement of private financial intermediaries; (*iv*) the type of user access to CBDC, either through accounts or tokens, which relates to an ongoing debate on privacy issues and transaction traceability; and (*v*) the needed infrastructure, i.e. whether blockchain technology can bring effective improvements in the opted design/system.

4.1. Nature and availability of CBDCs

As implied above, not all CBDCs can be created equal. When it comes to their particular characteristic and attributes (CPMI, 2018) highlight that "it is easier to define a CBDC by highlighting what it is not". With regard to the choice between a CBDC that is distinct from reserves (nR CBDC), and a one that pertains to the expansion of the reserve system to the wider private sector (R CBDC), there are compelling reasons to pursue either option. Reserves have a special status in the monetary system as they are subject to rules and limitations and serve as settlement asset for interbank transactions. Owing to this, they also represent the safest form of money in an economy. For that reason, a reserve CBDC that pertains to their expansion would be very safe, although not flexible. In contrast, while any CBDC necessarily leads to the expansion of the CB balance sheet, CBs can back CBDCs that are distinct from reserves with a different collection of assets, potentially making them less secure, but more flexible, than reserves. A non-reserve CBDC could be less safe if backed by more volatile CB assets, such as more risky financial instruments compared to precious metals or foreign exchange (Kumhof & Noone, 2021).

Flexibility in non-reserve CBDCs also comes in other forms. As demonstrated by Kumhof and Noone (2021), remuneration in the case of a non-reserve CBDC can be independent than that of reserves, leading to greater flexibility in the conduct of monetary policy. For example, CBs could keep the rate of reserves low to influence the market interest

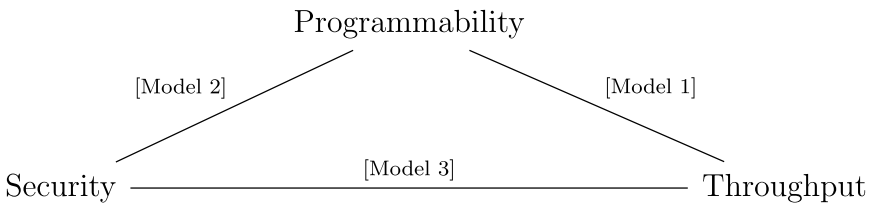


Fig. 1. CBDC programmability trilemma.

rate on interbank loans, while at the same time increasing the CBDC interest rate to curb CBDC demand. A non-reserve CBDC can pay positive, negative, or even no interest, without limiting the CBs options. At the same time, distinguishing CBDC from reserves can allow them to pursue different design choices, such as infrastructure and access methods.

Literature also distinguishes between three levels of CBDC availability. Those are, from more to less restrictive, wholesale, retail, and universal CBDC (-W, -R, -U, CBDC, respectively). Like CB reserves, a wholesale CBDC would be a liability of the CB and asset of appointed entities, such as commercial banks or other non-bank financial institutions (NBFIs). By contrast, a retail CBDC would also be available to the wider domestic private sector, meaning individuals and households. Finally, a universal CBDC would be the most expanded version, also available to the foreign sector.

CPMI (2018) were among the first to distinguish between wholesale and retail CBDCs. As the name suggests, wholesale CBDCs would be devised for wholesale applications between commercial banks, as well as NBFIs. Retail CBDCs on the other hand would be suited for retail applications, such as payments and domestic remittances and money transfers. Finally, a universal CBDC as described by Bjerg (2017) and Fung and Halaburda (2016) would allow individuals to hold and transact in different currencies at the retail level.

CPMI (2018) suggest that an interoperable wholesale CBDC could foster the robustness and efficiency of cross-border settlement of securities and other financial instruments. Their argument has become popular with policy makers, such as ECB's president Cristine Lagarde who stated that "Digital wholesale money is not new, as banks have been able to access CB money for decades. But new technology can be used to make settling financial transactions more efficient. It also opens the possibility of a retail CBDC, which would be very innovative in that it would be accessible to a wide audience" (Lagarde, 2020).

A wholesale CBDC could enhance payment efficiency, not necessarily due to its technical characteristics,[20] but by introducing a clean slate for wholesale and cross-border functions, allowing for their more efficient design, by reducing red tape and streamlining processes (Carney, 2019).

Notably, literature does not distinguish between a wholesale CBDC that is distinct from reserves, and a wholesale CBDC that simply pertains to the expansion of the reserve system to other entities. In this dichotomy, the question is whether having a wholesale CBDC distinct from existing reserves could be useful. We argue that depending on its monetary and technological characteristics, a non-reserve wholesale CBDC serve as a fail-safe and can be used alongside reserves by commercial banks. For example, a wholesale CBDC that utilises a different infrastructure from reserves could enhance the resilience of the banking system. CPMI (2018) also highlight that a creditworthy wholesale CBDC, especially if remunerated, could serve as an appealing asset for NBFIs and other institutional investors and compete with financial instruments such as short maturity government bills, with implication for on commercial banks' funding.

By contrast, a retail CBDC serving as an instrument for consumer-facing applications could result in an expanded role of the CB in retail functions and partial or entire disintermediation of commercial banks depending on its provision and other features. Owing to its retail nature, such CBDC could compete with commercial bank money, leading to changes in the funding composition of commercial banks, especially in times of stress (CPMI, 2018).[21] However, it could also promote positive change for households and individuals. Indicatively commercial banks, as for profit institutions, are incentivised to only extend financial services when they can make a profit. A retail CBDC, issued by a non-for-profit CB could be particularly important in facilitating financial inclusion in developing and underdeveloped economies where the private sector lacks the universal provision of robust payment services (Kiff et al., 2020).

A reserve retail CBDC would be the safest form of money that could be made available to the private sector. However, as noted above, it would come at the expense of monetary policy flexibility, since CBs would have to consider retail clients when implementing changes to reserve remuneration and holding requirements. Instead, a non-reserve retail CBDC, while potentially less secure from a financial standpoint, could provide a third monetary level (besides holding requirements and interest) for central banks, while also serving retail functions for the wider private sector.

A universal CBDC, as described by Bjerg (2017) and Fung and Halaburda (2016), could enable what (Auer & Boehme, 2020) describe as "retail interlinkages" for cross-border payments. Currently, digital transactions in a foreign currency necessarily involve one or more financial intermediaries who imposes fees and inflated exchange rates. This process also often leads to delays due to the number of counter parties involved in the process. With a universal CBDC end consumers would be able to acquire foreign currency in advance of the transaction potentially for cheaper, as is currently the case with cash. This advancement would be similar to current fintech and eMoney deployments by the private sector that allow customers to hold and exchange currencies in digital wallets. Yet, as a universal CBDC would be a liability of the CB, it would not be subject to the same counterparty and financial risks of eMoney and digital wallets.

Depending on its remuneration and issuing authority, a reserve universal CBDC, could also offer a compelling store of value in certain international markets and even compete with domestic short term government bonds and other private sector financial instruments, such as savings accounts. In times of crisis, universal CBDCs could also aggravate bank runs, not from deposits to cash as is usually the case, but from deposits to what is essentially a foreign currency. The same

[20] In fact, the benefits of blockchain/DTL for efficiency and robustness have been refuted mainly (*i*) due to the probabilistic finality of settlements in some blockchain/DLT arrangements, meaning that transactions are never fully settled, but only become increasingly hard (more costly) to reverse as more blocks (transactions) are added, (*ii*) the need for centralised notaries that make the added complexity of DLT redundant, (*iii*) and the potential implementation of coordination mechanisms such as systems for liquidity saving (Chapman et al., 2017; Chiu & Koeppl, 2017).

[21] This is explored further in Section 5.

could be said for a non-reserve universal CBDC, although those will likely be less "safe" compared to a reserve counterpart.

4.2. Direct, indirect, and hybrid CBDC provision

As outlined in Section 3, in the second exploratory phase of CBDCs motivated predominately by advances from the cryptocurrency and blockchain space, CBs and researchers examined alternative CBDC designs as potential sources of financial safety as well as efficiency and resilience of the financial system. The exploration revolved around three key areas: (*i*) the specifics of CBDC provision and in particular, the operational role of the central and commercial banks as well as other financial intermediaries, (*ii*) the method for accessing CBDCs and authorising transfers, and finally (*iii*) the ledger and process for recording said transfers and other state transitions. The overarching academic consensus was that (*i*) the operational role of the CB influences the financial safety of the CBDC instrument in addition to aspects of customer experience, (*ii*) the access method could impact the levels of privacy and anonymity of CBDC transactions, and finally, (*iii*) that a new novel infrastructure could be a source of efficiency and desirable features for CBDCs.

Auer and Boehme (2020) focus on a CBDC with retail applications and map six main consumer needs, to specific CBDC design choices, forming a Maslow-like hierarchy for payments. In particular they identify the needs for cash-like convenience and peer-to-peer functionality, resilient and robust operations, universal accessibility and privacy, as well as the need for cross border payments. A public consultation conducted by the Eurosystem on the digital euro (EU's version of a CBDC) identified privacy, security, lack of fees, availability, ease of use, and speed as the most important consumer demands (ECB, 2020). Similar consumer needs are also outlined in a joint report by seven CBs representative (Group of Central Banks, 2020).

Literature identifies three distinct models, the (*i*) direct, (*ii*) indirect, and (*iii*) hybrid, (- -D, - -I, - -H CBDC, respectively). According to Adrian and Mancini-Griffoli (2019), Auer and Boehme (2020), and Bordo and Levin (2017), a direct CBDC is a direct liability of the CB and asset of the private sector. In the case of a wholesale CBDC this would mean that banks and NBFI would hold a direct liability of the CB. Similarly, in the case of retail or universal CBDCs, households and individuals would hold a direct claim with the CB. Under a direct CBDC model the operational role of the CB would be that of the primary operator of a CBDCs infrastructure and all of its consumer-facing aspects. Indicatively it would be tasked with acquiring and retaining (wholesale or retail) clients, performing due diligence, including know-your-customer (KYC), AML, and CTF checks, or otherwise managing customer data, transactions and complaints or other inquiries. On the operations side, it would be charged with developing and managing the technology necessary for payments and their settlement, as well as other consumer facing features and applications (Adrian & Mancini-Griffoli, 2019).

The option of a direct CBDC is attractive for its seeming simplicity, as the private sector holds a secure, direct claim with the CB bank which is responsible for the entire CBDC's operation. Yet it incubates the disintermediation of commercial banks and other financial intermediaries[22] (Auer et al., 2022; Carstens, 2022). Such scheme would entail a large expansion of the CB mandate, the costly building of a vast infrastructure, and the CB's need to acquire consumer-focused skill. Besides the obvious point of cost, this expansion is also tied to concerns around the willingness and ability of CB to compete with existing and future private sector deployments, and the crowding out of the private sector (Auer & Boehme, 2020; BoE, 2020; ECB, 2020; Group of Central Banks, 2020). Finally, to support a CBDC (although this is a concern in every provision method), the CB might be incentivised to engage in credit provision to support their expanded balance sheet, further increasing its role and involvement in the financial system.

An indirect CBDC is comparatively a more modest proposal, in which the private sector (consumers in the case of a retail and universal, and NBFIs in the case of wholesale CBDCs) hold accounts with commercial banks, which are backed by CBDC held with the CB (Auer & Boehme, 2020; Bordo & Levin, 2017). This scheme has been described with various names in literature, such as "synthetic CBDC" (Kumhof & Noone, 2021), and "two-tier CBDC" for its resemblance to the existing two-tier financial system. An indirect CBDC presents a number of possibilities. In what we will call "strict indirect CBDC" a commercial bank would be required to fully back private sector deposits CBDC held at the CB. By contrast, in a "relaxed indirect CBDC" model private sector deposits would be partially backed by CBDC. The non-reserve versus reserve status of CBDC enters this discussion too. Specifically, in either the "strict" or "relaxed" indirect CBDC private sector deposits could be backed by either a CBDC that is distinct from reserves, or reserves with the CB. In the latter scenario, a CBDC would essentially be either a reinvention of the existing two tier system, or simply constitute a stricter version of existing reserve requirements.

In either case, commercial banks would have the same consumer-facing and operational responsibilities as they do today. Due to its minimally disruptive nature, an indirect CBDC would not translate into material improvements for the private sector, especially in terms of protection. For instance, in case of insolvency of the commercial bank, it is unclear how a CB would honour consumer claims. Deposits up to a certain amount are already guaranteed in many countries, thus rendering an indirect CBDC redundant. At the same time, and according to many definitions including the one in the present, an argument can be made that such arrangement would not constitute a CBDC in the first place, as is not a direct liability of the CB and asset of the private sector (Group of Central Banks, 2020).

Auer and Boehme (2020) also describe a hybrid CBDC arrangement in which consumer-facing activities are carried out by financial intermediaries, such as payment service providers (PSPs) and commercial banks, while the CBDC remains a direct claim with the CB. This approach marries the safety stemming from a direct claim with the CB with the convenience of the private sector managing consumer-facing functions. A hybrid arrangement could also implement a "check pointing" system in which the CB would periodically record end-consumer balances to ensure that claims are honoured in case of technical and financial failure of a PSP. Other back-up arrangements where the CB would operate an emergency transaction system can also be envisaged. Yet, as Auer and Boehme (2020) point out, the downside of a hybrid approach would be the complexity of its implementation. Most CB are considering to opt for a hybrid indirect CBDC (Auer et al., 2020).

4.3. CBDC access

With regard to access to the CBDC, two methods are currently debated: the account and the token-based methods. Account CBDCs rely on "strong" and verifiable identities, whereas token systems on an individual's ability to perform a specific action, such as demonstrate knowledge of a special value (BoE, 2020; Brunnermeier et al., 2019; Kahn et al., 2019). King (2020) report that among the 46 central banks in their survey, 58 percent focus their research on a "token model"

In particular, an account-based CBDC would operate in a similar manner to checking accounts with commercial banks where access relies on an individual's ability to veritably prove that they are the account holder (e.g., with a password or other form of identification). For that reason it can be thought of as a "I am, therefore I own" system (Auer & Boehme, 2020; Bossu et al., 2020). By contrast, a token-based CBDC would be more akin to a bearer instrument, such

[22] Explored further in Section 5.

as cash. In such scheme, individuals perform actions to (*i*) verify the payment object's (CBDC) validity and (*ii*) the counterparty's authority, or access over the payment object. In the case of many cryptocurrencies this amounts to producing and verifying a digital signatures utilising a public and corresponding private key. More specifically, transactions are initiated by "signing" information about the payment object and transaction instructions with a secret private key. The validity of the transaction (and the payment object) is verified when the signer's corresponding unique public key is compared to the signature generated by the private key. This is possible due to a mathematical relationship between the private and public keys that allows for the validation of the signature only against the public key (Antonopoulos, 2014). Knowledge of the private key (represented as an alphanumeric value) enables full access to the underlying asset, therefore token-based systems can be thought of as "I know, therefore I own" systems (Auer & Boehme, 2020; Bossu et al., 2020), and bearer investments, as whoever "bears" the private key "bears" the payment instrument. The main concern associated with account-based CBDC is identify theft or impersonation, whereas loss of keys is an issue in token-based solutions.

Account and token CBDC deployments would also differ in terms of their accountancy, and their introduction would likely necessitate changes in the legal and accounting frameworks to accommodate those. Account-based CBDCs, as existing checking accounts, would be minimally disruptive and follow the rules of double entry accounting. Balances would be recorded in accounts and transactions would work by debiting the payer's account (assets) and crediting the payees account (assets). By contrast, token-based systems come with "built-in" accounting in the form of an unspent transaction output (UTXO). In a token-based CBDC UTXOs would represent a certain amount of CBDC value that can be spent by a specific private key. When a UTXO is spent, it is "destroyed" by a new one, that can be spend with a different private key. This association of private keys with UTXOs constitutes a novel system for keeping track of balances without the use of accounts or balance sheets.

The three primary considerations in the token versus account debate relate to privacy/anonymity and cash-likeness. Cash has value to consumers because it is by nature anonymous, thus protecting individuals' privacy (Kahn & Roberds, 2009). Garratt and van Oordt (2021) discuss privacy in payments. Because of their non-reliance on 'strong identities' token-based CBDCs were initially promoted as private/anonymous alternatives to accounts, as well as more cash-like, as transfers would not involve the debiting and crediting of accounts, but rather the peer-to-peer transfer of tokens (Auer & Boehme, 2020; Bordo & Levin, 2017; Bossu et al., 2020; Claussen et al., 2021; Kahn & Rivadeneyra, 2020). Yet, as BoE (2020) and Claussen et al. (2021) demonstrate, complete anonymity/privacy and cash-likeness in CBDCs is likely unattainable. Claussen et al. (2021) identifies the three main factors for this: (*i*) First, the fact that digital processes necessarily produce digital fingerprinting which, given enough time and resources can be traced back to the counterparties in the transaction. (*ii*) Second, the need for a remote ledger to facilitate the notarisation of transactions, which would, even for some time store information that could be used to identify the counterparties of a transaction. (*iii*) Finally, regulation is likely to necessitate the involvement of the CB as a notary, and requires that under certain conditions the identities of individuals enmeshed in transactions must be known to facilitate KYC, AML and CTF. Indeed, in a first report published by a consortium of central banks, complete anonymity for CBDC is deemed "not plausible" (Group of Central Banks, 2020).

4.4. CBDC infrastructure

The advent of blockchain and cryptocurrencies motivated the exploration of alternative CBDC infrastructures as sources of efficiency and novel features. The debate resolves around the use of conventional databases and real time gross settlement systems, versus DLT/blockchain. See Auer and Boehme (2020), Benos et al. (2017), Danezis and Meiklejohn (2015) and Scorer (2017).

As with many new technologies there is a lot of confusion surrounding DLT/blockchain and what exactly they pertain to. Studying the writings of Haber and Stornetta (1991) and Nakamoto (2009) and the Ethereum (Buterin, 2014) and Hyperledger (Androulaki et al., 2018) whitepapers as well as Antonopoulos (2014), we will define blockchain as an append-only data structure where information is grouped in sets, called "blocks" with each block cryptographically referencing, through a hash function, forming a "chain". This data set is distributed in a network of peers who can independently verify its validity while its updating is subject to special rules. DLT is a superset of blockchain as references data sets that do not necessarily utilise cryptography (hashes) to link information together. We use both terms interchangeably in the present.

Notably, DLT/blockchain can accommodate either an account or token/UTXO CBDCs, as is the case in Ethereum and Bitcoin respectively. In a private setting it can also support a direct, indirect, and hybrid provision CBDC scheme depending on the participants' authorisation levels. Similarly, databases are also suitable for direct, indirect, or hybrid CBDCs (by changing participant's access levels), account CBDCs (as is currently the case with customer accounts at commercial banks) and even token/UTXO CBDCs, since under such scheme, a token/UTXO CBDC would in essence be "a chain of digital signatures" stored in a database instead of DLT/blockchain (Nakamoto, 2009).

DLT/blockchain has been studied as a potential source of efficiency, especially in terms of reducing reconciliation and data management costs by automating or streamlining, clearing, offering greater transparency, and tamper evidence (see for instance Chiu & Koeppl, 2019; Morgan Stanley, 2016; Santander, 2016, and Ruttenberg, 2016). Yet the overarching academic consensus is that the above are not necessarily hindered by the choice of technology, but by existing processes (Benos et al., 2017; Board of Governors of the Federal Reserve System (U.S.) et al., 2016). Additionally, DLT/blockchain deployments come with a number of drawbacks that mostly relate to scalability.

At this point a distinction needs to be made between private and public deployments (Dinh et al., 2017). While the data structure and its organisation remains the same, in public blockchains, network participants are usually unknown and mutually distrusting nodes that are economically incentivised to achieve consensus on state of the data set in a process secured by cryptography and game theory. This process is associated with significant overhead costs and hinders scalability to the point that a public DLT/blockchain deployment would be unsuitable for the volumes of a CBDC (especially its retail and universal variants) (Auer & Boehme, 2020; Budish, 2018; Chiu & Koeppl, 2019). Indicatively, for validating and submitting new blocks, Bitcoin (the most popular cryptocurrency by most measures) utilises Proof-of-Work (PoW), which involves the computationally intensive solving of cryptographic puzzles (mining) by special nodes called "miners". PoW, in conjunction with restrictions on block size and production frequency to facilitate accessibility to a wider audience, translate to a throughput of about seven transactions per second (Antonopoulos, 2014; Nakamoto, 2009). Ethereum, another popular public blockchain utilises Proof-of-Stake (PoS), which despite being more efficient compared to PoW, owning to artificial limits in block size and production to facilitate accessibility, can only process between 15–30 transactions per second. "Public" blockchain deployments that achieve higher throughputs have compromised on decentralisation or security, forming the popular blockchain trilemma, between scalability, security, and decentralisation.

Faced with this trilemma, CBs will opt for scalability and security over decentralisation (see for instance BoE, 2020; ECB, 2020; Group of Central Banks, 2020). Benos et al. (2017) and Danezis and Meiklejohn (2015) describe how some amount of centralisation will be necessary in a CBDC scheme to mitigate the overheads of distributed consensus. In fact, blockchain was rejected by China as it cannot accommodate the volume of transactions required for a CBDC (Gigichina, 2022). Databases are the more intuitive option as participants are known

(usually vetted) and securing and updating the data set can rely on their access-level, role and other business incentives, instead of inefficient consensus mechanisms. Additionally, those participants can have access to specialised hardware and software to facilitate the fast processing of transactions and state transitions, as is currently the case with commercial banks and PSPs. Databases remain an intuitive choice when other aspects such as resilience and vulnerabilities are considered, since DLT/blockchain does not necessarily constitute a material improvement and comes with its own set of trade offs.

That is not to say that DLT/blockchain can be made more, or even entirely, centralised to accommodate for a CBDC function. CBs could opt for a Proof-of-Authority (PoA) mechanism that relies on a small set of trusted and reputable entities to act as transaction validators and update the ledger (Wood, 2015). In the case of a direct CBDC, there would be a sole validator, the CB, whereas in the case of an indirect or hybrid CBDC, commercial banks and other PSPs would also have validator rights. Yet, such scheme would largely constitute a reinvention of the existing processes, but with extra steps rendering the use of DLT/Blockchain redundant as its "main benefits are lost if a trusted third party is still required" (Nakamoto, 2009). Yet, as explored in Section 3.2.3 in the context of programmability DLT/blockchain might offer benefits as it could allow for native execution of open-source code originally intended for decentralised blockchains, potentially yielding cost-savings in development time. In the interest of preserving space, the CBDC design tree is included in Appendix.

5. CBDCs, monetary policy and financial stability

5.1. CBDCs and monetary policy

CBDCs can certainly have a wide potential impact on the financial landscape. Hence, announcements related to CBDCs plans and advancements move financial markets, as demonstrated by Wang et al. (2022). They introduce two indices, the CBDC Uncertainty Index (CBDCUI) and the CBDC Attention Index (CBDCAI), derived from over 660 million news-stories, and demonstrate that financial assets, including cryptocurrencies, foreign exchange rates, and even traditional safe-haven assets like gold, show higher volatility in response to CBDC news. In this section we elaborate on the possible impact of CBDC schemes on monetary policy and financial stability.

In particular (Davoodalhosseini et al., 2020) summarise the main ways in which a CBDC could improve monetary policy, categorising them in "proactive" and "defensive". Under proactive arguments, they outline how a CBDC can facilitate the effectiveness, implementation, and transmission of monetary policy, as well as help stimulate the economy when necessary. By allowing for differentiated interest rate schemes dependent on the size of the deposit balance, incentivising consumers to maintain efficient levels of liquidity and minimising opportunity cost. Additionally, a CBDC's substitutability with deposits could improve the transmission of monetary policy as any change in remuneration would be more quickly and accurately reflected to other consumer rates. Finally and in conjunction with the phasing out of cash or high denomination notes, a CBDC could eliminate the zero lower bound, incentivising spending when needed. However, the authors point out that quantitative estimates of such benefits are limited, and there are ill-understood caveats associated with the elimination of the zero lower bound and the discontinuation of cash or the imposing of other restrictions. Additionally, such measures might blur the line between monetary and fiscal policy.

In terms of defensive arguments, the authors outline that a CBDC could preserve the effectiveness of monetary policy and safeguard the financial sovereignty by reducing consumer incentives to adopt alternative or competing monies, not denominated in the national currency. Such potential adoption would depend on the national currency being perceived as (i) financially risky or unstable (due to inflation or other factors), and/or (ii) severely lacking in features compared to other public or private monies. Naturally, such a scenario is unlikely in a stable developed economy with a healthy financial system.

Besides offering an overview of the ways CBDCs interface with monetary policy, the above also highlights the most important components of a CBDC when it comes to monetary policy, namely, its ability to bear positive and negative interest, wholesale, retail, or universal availability, and convertibility with other monies. In this section, we will analyse those considerations in further detail.

5.1.1. Interest rate considerations

As noted, the choice of whether a CBDC should bear interest is crucial. Depending on the economic cycle, this interest can be positive, zero or even negative. The concept of paying interest on short-term CB liabilities was first proposed by Friedman (1960), who suggested that an equivalent rate to the risk-free rate should be paid in order to make sure that the cost of holding money is equal to the marginal cost of its production. Keister and Sanches (2021) posit that a remunerated CBDC can serve as a new monetary policy tool that can be used to influence the efficiency of exchange and aggregate investment. The optimal interest rate depends on the characteristics of the CBDC and of other payment methods it is in competition with. As suggested in Meaning et al. (2018), interest paid can very depending on the entity that bears the CBDC instrument. For instance, CB might wish to offer different remunerations for commercial banks, NBFIs, or individuals and households to achieve different policy goals. Different interest rates can also be charged based on the size of CBDC holdings (Meaning et al., 2018). This argument favours a CBDC that is distinct from reserves, allowing for greater flexibility. In a system that is non-distinct from reserve, if the CB charges different interest rates for different reserve holders, this would *de facto* break their fungibility and create a two tiered CBDC system, of reserve-like and non-reserve CBDCs.

Bordo and Levin (2017), who consider CBDC and reserves to be distinct, suggest that the introduction of a remunerated CBDC may provide a unique opportunity to reform the existing monetary policy framework. In a growing economy with a stable price level, the interest rate paid on CBDCs would be positive. However, if the economy were to be exposed to a major shock, it would be possible for the CB to reduce interest rates as required (even to negative levels through demurrage fees) in order to stimulate economic growth and promote price stability. However, the effectiveness of negative interest rates is hindered by the use and circulation of cash money because cash would become more attractive when nominal interest rates approach zero and especially when they turn negative. This is supported by Agarwal and Kimball (2015), Goodfriend (2000), and Rogoff (2016) who propose that replacing cash with a CBDC could make it simpler to set a negative rate on CB money and thus bypass the zero lower bound. Nevertheless, as these authors acknowledge, the elimination of cash is not an essential outcome of CBDC. Bordo and Levin (2017) also note that interest rates can facilitate the establishment of a constant price level target that would serve as a natural focal point for expectations and a nominal anchor. Additionally, nominal interest rate adjustment on CBDCs could replace other monetary policy techniques (such as QE) as the primary monetary policy tool.

Finally, a (positively) remunerated CBDC could facilitate a more competitive financial system ensuring that government-issued money bears the same return as other risk-free assets and providing an incentive for depositors to shift funds into CBDC accounts over less competitive private sector institutions. Andolfatto (2021) and Chiu et al. (2019) study the financial implications of this more competitive landscape, noting that it does not necessarily hinder credit provision and bank funding, but does reduce monopoly profits, whereas Mancini-Griffoli et al. (2019) warn that remunerated CBDCs could result in increased

loan interest rates and diminishing credit demand.[23] Moreover, providing wide access to the CB's balance sheet through a retail or universal CBDC and offering market participants an interest rate could more effectively guarantee that no entity would lend at a rate lower than the floor, thus making the floor a more effective limitation (Meaning et al., 2018).

5.1.2. Technological availability considerations

When a CBDC is available to more entities in the private sector, it allows for a direct implementation of monetary policy, without relying on the existing monetary transmission mechanism (Bordo & Levin, 2017). This argument is based on the idea that decisions concerning the remuneration and convertibility of a CBDC can be more influential when more economic agents have access to it. Therefore, altering (increasing or decreasing) the interest rate, or convertibility (by limiting or expanding it) of a wholesale CBDC would be less impactful compared to doing the same for a retail or universal CBDC.

Additionally, Meaning et al. (2018) suggest that with a retail CB, the demand curve for electronic CB money could become less or more volatile depending on the positive or negative correlation of shocks affecting new market participants with those of existing participants. In the case of a positive correlation, more active management of the demand curve by CB would be required, whereas, in the case of a negative correlation, the demand curve would become less volatile, requiring less intervention. Finally, the more available a CBDC is, the more the CB's balance sheet can expand (Bindseil, 2020) with important implications for the financial system, such as those seen with quantitative easing (Plosser, 2019).

5.1.3. Convertibility considerations

Convertibility of a CBDC for other monies is an important attribute that influences monetary policy. With convertibility here we mean the ability for a CBDC holder to exchange it with other forms of money, such as deposits and cash, at face value. Naturally, at-par convertibility with every form of money (for instance eMoney, crypto, or foreign currencies) cannot be enforced, but in the case of deposits and especially cash it can be desirable. For instance, absent at-par CBDC convertibility with deposits or cash, any changes in the interest rate of a CBDC would not influence deposit rates or cash demand as strongly as in the case of convertibility at par. On that note, Agarwal and Kimball (2015) and Assenmacher and Krogstrup (2018), and later (Kumhof & Noone, 2021), argue for a dual-fiat currency system relying on flexible exchange rates between CBDCs, cash, and deposits, to facilitate financial stability and overcoming the lower bound.

Meaning et al. (2018) on the contrary, argue that the ability of depositors to convert commercial bank money into CB money on demand is essential for preserving confidence in bank deposits whereas, Kumhof and Noone (2021) counter-argue that it is high regulatory oversight and compliance requirements rather than guaranteed convertibility of financial instruments which drive confidence in the commercial banking system. Although there is no concrete evidence to support either position conclusively, certain events from the 2008 financial crisis as well as capital controls imposed in Greece and Cyprus during the Eurozone debt crisis provide strong arguments both for increased oversight and direct convertibility. Moreover, as we will demonstrate in the next section, Kumhof and Noone's suggested CBDC is of arguable utility to the wider private sector, in part due to their non-convertibility requirement.

Meaning et al. (2018) offer another argument in favour of direct convertibility. The authors note that in certain scenarios excessive QE has resulted in commercial banks holding an excess of reserves, which in a case of a CBDC that is non-distinct from reserves could be used for asset purchases from the private sector. This would not be directly possible in a CBDC scheme that is distinct from reserves (like the one proposed by Bordo & Levin, 2017). Instead, commercial banks would need to first switch reserves for CBDC (either with the CB, or other private entity) before offering it to other entities in the private sector.

5.1.4. Other considerations

Davoodalhosseini (2022) examines the optimal monetary policy under a cash-only, CBDC-only and a dual cash-CBDC regime. In their model, a CBDC is interest bearing and users incur a (technological) cost for using it. At the same time, due to its remunerated electronic nature, a CBDC can improve the efficacy of "helicopter drops". Assuming that the CBDC perfectly substitutes cash and its cost is low, the optimal policy is to abolish cash.

Conversely, if the CBDC cost is set too high, the model predicts that only cash should be used. In the case of co-existence, if the cost of utilising CBDC is not too high, the optimal policy would be to use only one form of payment. This is because if both cash and CBDC are allowed to co-exist, and are perfect substitutes, consumers may decide to use cash in order to avoid taxes associated with CBDC, leading to an underutilisation of the attractive feature that CBDC offers — bearing interest. If cash and CBDC are not perfect substitutes, co-existence can be optimal.

Barrdear and Kumhof (2022) consider a similar scenario where deposits and CBDC are not perfect substitutes. The authors find that the introduction of a CBDC increases the steady-state GDP through reductions in real interest rates, distortionary taxes, and transaction costs, due to a reduction of defaultable debt, cost of government financing, and increased liquidity respectively. Additionally, a CBDC expands the monetary policy toolbox by offering an additional policy lever in the form of the interest it pays. Finally, Chen and Siklos (2022), examine the potential impact of CBDC on inflation and financial stability using historical data and McCallum's policy rule. Their model predicts that while CBDC is unlikely to result in higher inflation, there is a risk to financial stability. It also suggests that eliminating large denominations from circulation will not negatively impact inflation control, but does not advocate eliminating physical currency entirely.

5.2. CBDCs and financial stability

This section explores existing research on the potential impacts of CBDC on the financial system, contingent on the CBDC design, substitutability with other forms of public and private money, and any restrictions set in place to mitigate substitution between them, bank market power and more. In most cases, authors consider a hybrid CBDC solution. As highlighted in Section 4.2, this solution is the most intuitive as it allows each agent to focus on their core competencies, namely, the CB on providing access to safe money, and the private sector on handling customer relationships.

The literature so far has focused on how different designs of CBDCs will affect bank funding, deposits, lending, consumer welfare, and financial system fragility through bank runs. For instance, if a CBDC is highly substitutable for cash or deposits it terms of functionality, while paying higher interest and offering additional technological features, it could be desirable enough that consumers abandon alternative assets to use it — leading to disruption in the financial system. On the contrary, if a CBDC does not offer sufficient utility or substitute value compared to existing instruments then it would cause minimal disruption but may be redundant. Overall, a CBDC can improve allocative efficiency provided that their interest rate is reasonable. However, besides remuneration, CBDCs can compete with other monies across

[23] Explored in Section 5.2.

Table 2
Overview of papers.

Author	Model	Intstr.	Comp.	Design	I	Rd	Rl	Runs
Andolfatto (2021)	DD	X,C,D	M	nR,R,H,-,-	✗	↑	–	✗
Fernández-Villaverde et. al. (2021)	DD	X,D	M/C	-,R,D,A,-	N/A	N/A	N/A	✓
Kim and Kwon (2019)	DD	X,D	C	nR,R,D,A,-	✗	↑	↑	✓
Schilling et al. (2021)	DD	X,D	M/C	nR,R,D/I,A/T,-	N/A	N/A	N/A	✓
Chiu et al (2019)	LW	X,D	C	nR,R,D,A,-	N/A	↑	↓	✓
Keister and Sanches (2019)	LW	X,C,D	C	nR,R,-,-,-	✓	↑	↓	N/A
Williamson (2021)	LW	X,C,D	C	-,R,-,-,-	N/A	N/A	N/A	\cmark
Dong and Xiao (2021)	LW	X,C,D	C	-,R,I,-,-	✗	↑	↓	N/A

This table provides an overview of various papers examining the financial implications of CBDC implementation. Papers utilise different models which they apply to CBDCs with different characteristics. The columns report the author, the model being studied, the payment instruments examined, the competitive environment examined, the design of the CBDC, whether the CBDC impairs commercial bank income/funding, the deposit rate, the lending rate, and whether it can facilitate bank runs.
Model: DD: Diamond and Dybvig (1983), or variation, LW: Lagos and Wright (2005), or variation.
Instr: Payment instruments examined. X: CBDC, C: Cash, D: Deposits.
Comp: Competitive environment examined, where M: Monopolistic, C: Competitive.
Design CBDC: nR or R: Reserve or non-reserve. W, R, or H: Wholesale, retail, or universal. D, I, or H: Direct, indirect, or hybrid. A or T: Account or token. B or D: Blockchain or Database.
I: Impairs commercial bank income/funding.
Rd: Deposit rate, Rl: Lending rate, Runs: Can facilitate bank runs.

multiple dimensions, including safety, privacy, and novel features such as programmability, which remain largely unexplored in literature.[24]

Table 2 provides an (non-exhaustive) overview of relevant research articles, the models used and their often contradicting findings. Overall, there remains no definitive answer concerning whether there exists a design that offers tangible utility while also avoiding disruption across the financial system. This question is further compounded by the ever-evolving nature of research into this area along with numerous mutually exclusive design options available. Additionally, most studies concentrate on how CBDCs will affect commercial banking rather than non-banking entities. The latter could be particularly vulnerable given certain proposed designs where banks still have some minor role within the framework of certain CBDC systems. Finally, the role of wholesale CBDCs in financial disintermediation is not examined.

5.2.1. CBDC effects on deposits, funding, lending and consumer welfare in different competitive environments

Andolfatto (2021) and Chiu et al. (2019) examine the potential effects of implementing a hybrid remunerated retail CBDC, distinct from reserves, on bank lending and funding activity, in an economy with a monopoly bank, and imperfect competition respectively. In both cases, the introduction of CBDC gives consumers the option to hold deposits outside the traditional banking sector, creating competition between commercial bank deposit rates (Rd) and CBDC interest rates (Rc). Rational consumers typically opt for whichever rate is higher, assuming no technological advantages between CBDCs and deposits or disruptive financial events that make CB liabilities more attractive.

When the interest rate of reserves (Rr) remains below Rc ($Rr < Rc$), commercial banks have every incentive to match Rd to Rc to maintain customer deposits. This is because the commercial bank's cost of money is Rr and not Rc. As long as there remains a positive spread between these two rates, it pays for banks to retain deposits despite any reduced profit margins from raising Rd = Rc. Additionally, this potential rate increase leads to more favourable terms for depositors which expands financial inclusion.[25] Andolfatto (2021) observes no effect on bank lending in his model, as the opportunity cost for loans is determined by Rr instead or Rc. Chiu et al. (2019) underline that a CBDC might increase bank lending due to the expansion in deposits. Dong and Xiao (2021) and Monnet (2021) also agree with the findings of Andolfatto (2021) in terms of Rd but deviate in terms of the impact on the lending rate.

Overall the main benefit of a CBDC is found in an imperfectly competitive deposit market, in which commercial banks limit the amount of deposits available in order to suppress Rd. The introduction of a CBDC establishes a floor rate for Rd = Rc, reducing bank's incentives to restrain the supply of deposits. As a result commercial banks offer more deposits, reduce loan rates, increase lending activity, and expand financial inclusion. This holds true so long as $Rc \leq Rr$. In a scenario where $Rc > Rr$ a bank would make a loss if they chose to maintain deposits, resulting in higher cost of funding for commercial banks, and suppression of deposits. Chiu et al. (2019) also caution that lending rates may increase in case commercial banks face liquidity constraints due to $Rc > Rd$. Andolfatto (2021) offers the additional insight that higher Rd resulting from increased competition could have disinflationary effects on the economy, while also offering more compelling terms for depositors and facilitating financial inclusion. Kim and Kwon (2019) find that the introduction of a CBDC suppresses supply of credit by commercial banks resulting in a higher nominal rate and lower reserve-deposit ratio also leading to an increased probability of bank runs.

Keister and Sanches (2021) study the introduction of a CBDC in a competitive bank market. They consider three distinct scenarios, a CBDC with a high degree of substitutability with cash, deposits, or both cash and deposits respectively and comment on the trade-offs of each. They find that if there is a strong incentive for financial inclusion, it is optimal to have a CBDC with a high degree of substitutability for cash. When the number of productive projects is limited compared to the demand for deposit-like money, then it may be advantageous to devise a deposit-like CBDC, particularly when financial frictions are moderate. If a CBDC can fulfil both roles simultaneously, its circulation could be either broader or more restricted than if it had high substitutability with either cash or deposits. Overall, while a CBDC always causes some disintermediation social welfare can still increase. Importantly, in the scenario of a CBDC with high substitutability with deposits, they arrive at the same conclusion as Andolfatto (2021) and Chiu et al. (2019), noting that increased competition raises Rd, and expands the commercial bank depositor base.

Their findings deviate from those of Andolfatto (2021), Chiu et al. (2019), and Monnet et al. (2021), to the extent that under perfect competition, commercial banks are unable to insulate themselves from changes in funding costs, since they already offer competitive Rd, and as a result pass their costs onto borrowers. This can lead to a decrease in

[24] Although Agur et al. (2022) explore the concept of privacy/anonymity.
[25] As consumers are more incentivised to bear the costs of opening a bank account.

aggregate lending and investment. Yet, when payment efficiency is low, introducing a CBDC may be sufficient for achieving gains in payment efficiency that could offset any losses incurred by reduced aggregate investment.

Similarly, Agur et al. (2022) and Keister and Sanches (2021) examine the welfare implications of introducing a CBDC. They consider a scenario in which consumers need to allocate their income between cash, deposits and a CDBC according to their preferences on the payment instruments' degree of security versus anonymity, positive network effects stemming from their widespread use, and remuneration (if any) *vis a vis* other instruments.

On the privacy-to-security spectrum, cash and deposits fall at the two extremes, with cash being entirely private and non-secure and deposits entirely secure but non-private. Instead, a CBDC is socially valuable as it can be designed to occupy any point in the privacy-to-anonymity-spectrum. The authors find that the more cash-like a CBDC is, the more it substitutes cash even causing its disappearance due to the lack of network effects stemming from its lower usage. On the contrary, a deposit like CBDC leads to increased competition with commercial banks and increased deposit and lending rates, before contracting credit provisions to firms.

The latter is in contrast to the findings of Andolfatto (2021) who concludes that assuming commercial bank market power and provided $Rr < Rc$, the commercial bank lending process is not hindered, and that the depositor base can even expand if the commercial bank accepts lower profit margins to retain customer deposits by matching Rd = Rc. Such an assumption is absent from Agur et al. (2022).

For Agur et al. (2022), interest paid on CBDC is seen as introducing distortions in consumer choice of payment instrument. Yet, the authors recognise the interest rate's utility in limiting the substitutability of CBDC with other monies, and in preserving consumer welfare by controlling payment instrument network effects. The authors also consider other political economy factors for an interest bearing CBDC which include the preservation of cash, limiting impact on bank intermediation, the introduction of CBDC after cash has fallen out of favour or when anonymous payment instruments create negative social externalities, and when banks have market power the optimal CBDC rate can deviate from zero.

5.2.2. CBDC effects on bank runs and financial disintermediation

On the point of disintermediation and deposits, Bindseil (2020), Kim and Kwon (2019), Mersch (2018), Schilling et al. (2020), and Williamson (2022), highlight the possibility of CBDCs facilitating bank runs in times of financial stress and Cecchetti and Schoenholtz (2017) suggest that unsophisticated consumers might exchange deposits for CBDC when the first signs of financial risk appear. While the authors recognise that tools to enable such bank runs exist today (for instance, cash or government debt) the digital nature of a CBDC could aggravate the switching. Additionally (Fernández-Villaverde et al., 2021) utilise the Diamond–Dybvig model to showcase how the CB can emerge as a monopoly depository institution. In their model, a non-fiscally backed CB has access to liquidity transformation (long term investment) through arrangements with investment banks and is able to replicate the socially optimal contract offered by commercial banks. Yet, if the CB were to receive fiscal backing it would monopolise deposits. Moreover, due to the CB's contract rigidity with investment banks (the CB cannot call on its investment) runs on CB are deterred. Consumers aware of this fact opt to deposit with the CB instead of commercial banks, leading it to become the monopoly depository institution. With its new monopoly power, the CB can deviate from the socially optimal contract.

Considering those effects, Kumhof and Noone (2021) envisage a minimally disruptive CBDC which: (*i*) would pay an adjustable interest rate, allowing for the market for CBDC to settle without the need for extensive balance sheet adjustments or changes in the general price level; (*ii*) be distinct from reserves, with no guaranteed direct convertibility to one another at the CB, so as to address the risk of a 'run by the back door' scenario; (*iii*) not be subject to guaranteed convertibility with bank deposits at commercial banks, so as to avoid runs on the aggregate banking system; and (*iv*) be issued by the CB only against eligible securities, such as government bonds, and strictly at its discretion.

They examine its potential first-order effects on commercial banks' balance sheets by considering the scenario of an initial introduction of a CBDC, and that of confidence crisis in the banking system, leading to an increased demand for CBDCs by households and individuals. If these principles are upheld, they conclude that in the first scenario: (*i*) The core functions of the commercial banking sector, namely, the provision of credit to borrowers and liquidity to depositors, are not impaired, despite diminishing deposits. (*ii*) Commercial banks and their customers, through their respective portfolio decisions, decide how much depositors switching to CBDC affects the size and composition of commercial bank balance sheets. (*iii*) Banks can still fulfil their traditional role as intermediaries. For the scenario of a loss of confidence in the banking system, we explain how the probability of a run from bank deposits to CBDC can be notably reduced by using the same core principles.

While the authors acknowledge the potential of CBDC to serve as the most secure form of money in the economy, their proposed restrictions may diminish this utility. For instance, under conditions of extreme financial stress, access to CBDC might be limited as a result of public and private sector actions. For example, decreased interest rates set by the CB (potentially even demurrage fees), refusal from commercial banks to convert government securities and deposits into CBDCs, or refusals from NBFIs and other private entities to exchange CBDC for deposits could reduce the appeal of CBDC as a safe instrument. It is thus uncertain if such a CBDC would be attractive or beneficial. Features such as anonymity and programmable payment capabilities may make it an attractive medium of exchange rather than only a safe asset; however, its competitiveness in this capacity against offerings from the private sector and its appeal to consumers remain debatable.

Other authors share similar concerns with Kumhof and Noone (2021) but have proposed less radical solutions. For instance, Fernández-Villaverde et al. (2021), Meaning et al. (2018), and Williamson (2022) posit that such concerns can be mitigated through deposit insurance schemes by the CB and Kim and Kwon (2019) as well as Brunnermeier and Niepelt (2019) argue that if the CB lends CBDC deposits to commercial banks it can reduce the risk on bank runs and improve financial stability. Bindseil (2020) outline how Kumhof and Noone (2021) proposed limitations might be redundant. They showcase how interest rate on CBDCs is not a necessary condition for market clearing or inflation control, instead suggesting that, similar to cash, a potential CBDC oversupply would be neutralised by returning to the CB which would then adjust reserves and open market operations accordingly. Similarly they question the choices of distinguishing CBDC from reserves and establishing non-convertibility outlining that similar schemes exist between cash and reserves. Overall they argue that in their attempt to create a minimally disruptive CBDC, Kumhof and Noone's suggestions disrupt the *status quo* and counter-propose other solutions. Similarly to Panetta (2018), they suggest limiting the amount of CBDC holdings per consumer, and even offering remuneration tiers depending on the amount of holdings to mitigate bank runs to CBDCs. Finally, they also note that the attractiveness of CBDCs also relies on other features, besides remuneration, while recognising that a remunerated CBDC would provide a useful monetary policy level for adjusting a CBDCs substitutability with other monies, a notion also echoed in Agur et al. (2022).

A strand of literature also suggests that concerns around the levels of commercial bank disintermediation might be exaggerated, and

measures such as those proposed by Bindseil (2020) and Kumhof and Noone (2021) might be redundant. Indicatively, Williamson (2022) posits that bank runs might be less disruptive under a CBDC regime whereas Keister and Monnet (2022) find that CBDCs might decrease financial fragility as the CB can monitor the flow of funds into CBDCs and identify weak banks giving policymakers more time to act, discouraging depositors to run on banks.

6. Arguments against CBDC issuance

While Section 2 has listed a number of arguments in favour of the introduction of CBDC, this section allows us to explain the existing counter-arguments against. The CBs tend to favour CBDC because they allow them to increase their control over the financial system and mitigate some of the existing financial risks.

Regarding motivations, recently, many CBs have placed great emphasis on issuing CBDCs in order to protect financial sovereignty, particularly against the issuance of foreign CBDCs. The theoretical arguments supporting this idea were presented in Section 3.1.3 and include the threat of currency substitution and bank runs to foreign assets. However, some of these concerns may be exaggerated. For example, Martin Chorzempa, a senior fellow at the Peterson Institute for International Economics, testified to the US–China Economic Security Review Commission on the threat of China's CBDC, stating that it has yet to demonstrate greater cost-effectiveness, efficiency, privacy, or convenience than other solutions, and is therefore unlikely to challenge the dollar's international dominance in the short to medium term (Kaminska, 2021). Additionally, Engert and Fung (2017) argues that the potential of a CBDC to reduce the effective lower bound and combat financial crime can be achieved through other means, such as the implementation of regulatory measures to promote competition in retail payments. Finally, Quarles (2021) notes how a CBDC may pose a threat to resilience by serving as a honeypot for cyber-criminals, due to its digital nature, large surface, and significance relative to other forms of money. Moreover (Bindseil, 2022) highlights that the alleged transformative potential of digitisation in money and payments, as well as CBDCs in particular, might be overestimated, citing the constant evolution of money and the relatively unchanged issues of commercial and central banking.

The proposed alternative infrastructures and design options discussed in Section 4.4 have yet to show a clear advantage over existing systems in terms of meeting the needs of both consumers and central banks. In fact, many suggested solutions would come with significant costs. For example, developing a new DLT/blockchain record-keeping infrastructure, or expanding the CB's role as the sole financial intermediary as advocated by direct CBDC schemes, would be costly and disruptive and less desirable. Additionally, the introduction of a CBDC would require educating consumers, who may be resistant to change, on its use and proper security practices. Even if accessing a CBDC requires minimal equipment, such as a smartphone, the CB would need to provide this for consumers who do not have it, especially if cash usage decreases.

The factors of cost and destabilisation have led many to abandon more radical CBDC schemes in favour of deployments that iterate on and do not replace existing infrastructure and schemes, with any additional features, such as programmability, likely offered as optional "add-ons", as outlined in Section 3.2.3. In academic research, most authors abstract away from CBDC infrastructure, as, for the most part, a CBDC that satisfies CB motives can be designed entirely within the boundaries of existing systems, particularly through adjustments of interest rates and the availability of a reserve or non-reserve CB liability to the private sector. This raises the question of whether a CBDC is truly a new payment instrument or simply a shift in policy to increase CB influence. Lastly, and importantly, despite the consumer need for cash-like privacy and anonymity, as discussed in Section 3.2.2, CBDCs can serve as a tool of mass surveillance, due to the concentration of information on citizens. Naturally, this lack of cash-like privacy and anonymity is another argument against CBDC issuance.

CBDC schemes involving the private sector are viewed favourably, with some (such as Bofinger and Haas (2020) and Engert and Fung (2017)) arguing that they can offer products and services that serve the same purpose as CBDCs while achieving higher customer satisfaction and lower costs. This is supported by the analysis of the direct and hybrid CBDC schemes in Section 4.2. Mobile payment services like Apple Pay, Google Pay, PayPal, AliPay, and WeChat Pay already handle trillions of transactions annually, and blockchain providers[26] offer CBDC-as-a-service, demonstrating the private sector's capability in providing solutions at a large scale. Additionally, proposals for scaling blockchain deployments such as rollups[27] can theoretically enable hundreds of thousands of transactions per second, potentially making stablecoins or even cryptocurrencies a viable solution for payments.

Furthermore, Engert and Fung (2017) outline several arguments against the issuance of a CBDC, even if it is designed entirely within existing boundaries. Chiefly, they note that central banks have been able to effectively influence consumer rates through the adjustment of the overnight rate, thus rendering the need for an additional monetary policy level redundant. Additionally, they argue that the ability of a CBDC to pay interest is incompatible with strong privacy and anonymity due to regulatory and tax considerations, noting that such remunerated CBDC would hinder any benefits to financial inclusion for individuals without access to strong identities. CBDC interest would also inhibit any marginal seigniorage gains in proportion to the level of the interest rate. Regarding the argument of using CBDCs to eliminate the zero lower bound, the authors warn that such a move would have significant political economy implications that may damage the reputation of the CB, in addition to impairing the welfare of less sophisticated consumers who might rely on such income. Finally, as we outline in Section 5.2, while most authors suggest that a reasonably designed CBDC can provide welfare benefits through increased competition, they simultaneously recognise that, absent that level of restraint, its implications for the financial system will be severe, including funding constrained commercial banks raising fees and rates for customers, and the disintermediation of large parts of the existing financial system. There could also be potential negative consequences and costs related to the widespread adoption of digital payment solutions by consumers with low financial literacy, but not much literature has been developed yet on this topic.

Overall, as the more radical schemes of total anonymity, decentralisation, and disintermediation have been abandoned in favour of more modest proposals, the above arguments suggest the potential redundancy of CBDCs.

7. Summary and future research

Nearly every CB in the world is examining the issuance of CBDCs and many at an advanced stage. CBDCs are therefore an eventuality whose impact is still unclear due to the complexity of their de-

[26] See for instance Consensys, Ripple, and nChain.

[27] Rollups are a blockchain scaling solution that utilises off-chain computations to increase scalability and throughput while maintaining the security of the underlying blockchain. Transactions are combined into a single "rollup" transaction which is broadcast to the main chain, enabling a higher transaction throughput.

sign and the implications for the financial system. It is essential that research keeps up to speed to avoid any of the discussed negative consequences of CBDCs. The extant literature reviews on this topic have followed a systematic approach and have been useful in organising the earlier knowledge. However, navigating the fast-growing research on CBDC can be particularly labyrinthine due to its pace and complexity.

This thematic literature survey provides a comprehensive handbook for understanding all CBDC aspects. First, we review the existing definitions and provide a universal one; we contextualise CBDCs as the latest in a line of key financial system's shifts; we analyse the arguments in favour of CBDC issuance instigated by contemporary financial events and trends requiring the introduction of new financial instruments. In particular, we look at the discussion around CBDC in response to the need for: a new monetary and fiscal policy tool, improvements in payment speed and efficiency, the safeguard to CB sovereignty with heightened competition from cryptocurrencies, the mitigation of the negative effects of declining cash usage and of increasing privacy-invasive private sector payment systems, and, finally, the development of programmable money and payments solutions.

Second, we examine the design space and options for CBDCs, including: their reserve or non-reserve status as a liability, wholesale, retail, or universal availability, direct, indirect, or hybrid provision, account or token access, and the choice of a novel DLT/blockchain or the use of the conventional real-time gross settlement infrastructure. We argue that the choice of infrastructure and access method are largely inconsequential. In particular, a token-based CBDC would not necessarily facilitate anonymity/privacy and a DLT/blockchain infrastructure would not always result in efficiency or resilience gains. We also demonstrate how, in certain cases, the opposite might be true.

On the contrary, the availability and liability-nature of CBDCs are, by contract, impactful for their monetary implications. We discuss the implications of different breadth of CBDC availability, its eventual interest-bearing nature, the convertibility with other monies, its impact on bank confidence and stability and competitivity. In particular, we note that a reasonably designed CBDC, bearing a modest interest rate, may not necessarily lead to financial system disintermediation. In this light, we also showcase some proposals for more conservative CBDC approaches. Finally, we present the primary arguments against CBDC issuance and focus on discussing their potential redundancy due to their progressively diminishing ambitious design.

In light of the literature reviews and the developed discussion, we identify several research priorities. First, we need further empirical studies on the motivations for CBDC issuance and the factors influencing CBDC adoption. While prior studies have employed qualitative methods, such as questionnaires administered to CBs, these may not always provide a comprehensive understanding of the underlying political and economic drivers and certainly cannot focus on the needs and opinions of the public (see for instance Bindseil et al., 2021 and ECB, 2021). Bijlsma et al. (2021) and Maryaningsih et al. (2022) utilise empirical methods to study the drivers of CBDC adoption considering the characteristics of consumers and the needs of the financial system. However, these studies can be expanded in a number of ways, for instance by considering how different CBDCs may appeal to different consumers or different scope of use.[28] The difficulty of this research question is compounded by the inherently complex nature of CBDCs, and in certain cases, even by the low financial literacy of the final potential users. However, the insights that can be derived by such study can be useful to analyse the demand for CBDCs, the disintermediation potential, and the most useful design.

Second, while some studies have attempted to predict the general CBDC demand (for instance, Li, 2022 and Burlon et al., 2022), such studies do not exist for the majority of advanced or developing economies. Notably, the volatility of CBDC demand potential, including its determinants, remain largely unexplored.

Third, in terms of CBDC infrastructure, we find programmability being an important and largely unexplored aspect (with some exception in the computer science literature). In particular, we need to study more which new capabilities digital centralised money programmability can offer and its implications on competition in the financial system as well as on consumer welfare. Additionally, researchers should examine the implications of CBDC programmability on environmental or sustainable goals. For instance, as outlined in Section 3.2.3, the introduction of a novel tax at the unit-level if a CBDC is spent on a carbon-intensive goods and services would influence consumer preferences, payment choices, and welfare.

Fourth, as discussed in Section 5, while the literature on the financial implications of CBDC introduction is growing, most authors focus on its effects on commercial banks, leaving out non-banking entities, such as eMoney and fintech providers, and stablecoin and cryptocurrency deployments. The latter may be particularly susceptible to the issuance of a CBDC, even more than commercial banks which, as most literature recognises, may preserve a role. Future research can start addressing this important gap in knowledge for example by looking at how announcements related to CBDCs developments influence the relative institutions and markets.

Fifth, in Section 5 we also underline how different CBDC schemes deployed in different competitive environments might influence financial stability. The overarching consensus is that there is a trade-off between CBDC utility and the level of financial disintermediation. The question of whether a CBDC that is both minimally disruptive for the financial system and maximally valuable for its users exists remains unanswered. Moreover, even if such a CBDC scheme does not exist, there is no definitive answer as to the optimal design options that balance the various benefits and costs.

Sixth, another potential research avenue is the study of how CBDC issuance – against other existing CB liabilities – might influence the CB balance sheet structure and how this can reverberate on the financial system. Importantly, to support a CBDC, especially in absence of restrictions such as those set by Kumhof and Noone (2021), the CB might be incentivised to engage in credit provision to support their expanded balance sheet, further increasing its role and involvement in the financial system. How this provision of credit would work in practice, and how it would influence the wider private sector is an important avenue for future research.

Seventh, as discussed in Section 3.2.2, the widespread adoption of a CBDC may potentially curb illegal markets and tax evasion. The extent of this curbing and its potential impacts on the financial system and tax revenues remain an area for further research.

CRediT authorship contribution statement

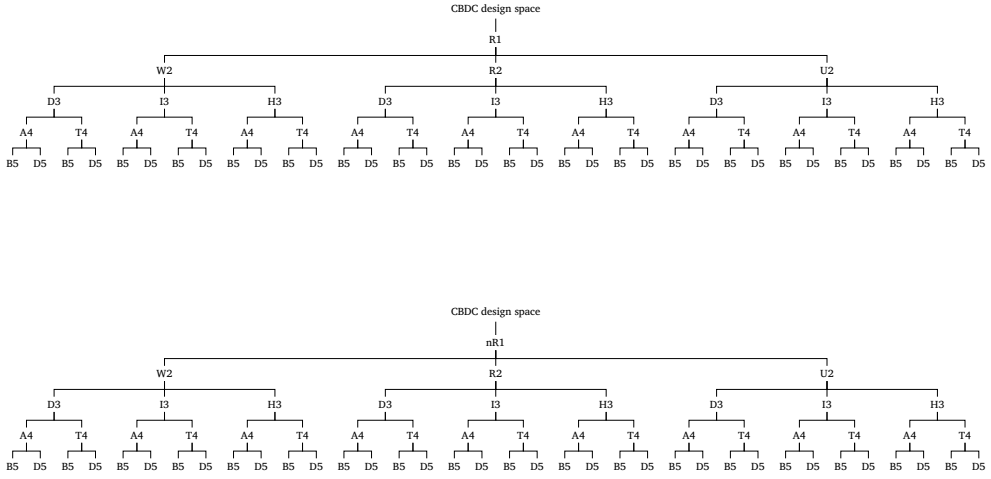
Lambis Dionysopoulos: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Miriam Marra:** Conceptualization, Writing – review & editing, Supervision. **Andrew Urquhart:** Conceptualization, Writing – review & editing, Supervision.

Data availability

No data was used for the research described in the article.

[28] The ECB's 2020 report on the digital euro (ECB, 2020) examines the desirable features of a CBDC by consumers; however, it does not address the question of whether consumers can derive any utility from a CBDC in the first place and, if so, what type.

Appendix. CBDC design space and options



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