EUBlockchain
Observatory and Forum

Central Bank Digital Currencies and a Euro for the Future

A Thematic Report Prepared By
The European Union Blockchain Observatory & Forum

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About this report

This is the second of a series of reports that will be published addressing selected topics in accordance with the European Commission priorities. The aim is to reflect on the latest trends and developments and discuss the future of blockchain in Europe and globally.

This report, prepared by the new team leading the EU Blockchain Observatory and Forum, aims to present Central Bank Digital Currencies (CBDCs) and design options for a digital euro.

This report has been produced by the EU Blockchain Observatory and Forum Experts Panel and team.

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Note

While we have done our best to incorporate the comments and suggestions of our contributors where appropriate and feasible, all mistakes and omissions are the sole responsibility of the authors of this report.

Disclaimer

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EUBOF: Central Bank Digital Currencies and a Euro for the Future

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Chapter 1: An Introduction to CBDCs

SECTION 1.1: OVERVIEW AND DEFINITIONS

Central bank digital currencies (CBDCs) have grasped the interest of central banks, policy makers, regulators, industry, and the general public, especially over the past year. The number of central banks actively engaging in CBDCs in one way or another, has increased from one third in 2018, to almost 90% as of March 2021.

This report aims to provide a foundational understanding of CBDCs, the factors that necessitate their issuance, and an overview of the events leading up to relevant initiatives, public tests and live implementations. We focus on a European CBDC (henceforth also referred to as the 'digital euro') to explore the design space of its possible future implementation.

The digital euro as the next evolution of the euro

Europe has a long history of developing and refining the infrastructure that underpins the European economy and enables an interconnected union. The introduction of the euro as the common currency of the Eurosystem in 1999 was accompanied by the establishment of a Real Time Gross Settlement System for Europe. **TARGET**, as it was called, was developed as an efficient, safe, and reliable mechanism for the settlement of euro payments that would support the ECB's monetary policy through the integration of money, and financial markets (European Central Bank, 2005).

In May 2008, TARGET was succeeded by **TARGET2**. The new system enabled even faster and more secure payments in addition to other advancements by replacing the decentralised structure and inconsistent technological frameworks of the first iteration in favour of a Single Shared Platform (Deutsche Bundesbank, 2018).

The TARGET Instant Payment Settlement, or **TIPS**, was introduced in 2018 as an extension to TARGET2. TIPS was a direct response to address the growing consumer demand for instant payments without reintroducing the complexity and fragmentation of national solutions. Among other upgrades, this new iteration offered even faster payments, enhanced resilience, and the ability for settlements in other currencies.

The common denominator of each new advancement is the promise of further speed and efficiency in payments, costs savings, pan-European coverage, and additional features to address the modern needs of consumers and the Central Bank. **A European Central Bank Digital Currency, or digital euro**, would be the next step in this evolution. By potentially tapping into new technologies and possibilities developed and nurtured in the open blockchain space, as well as innovations honed by the wider private sector, a CBDC can be a definitive step towards ensuring that the Eurosystem remains current in the rapidly changing global landscape. A lot of questions remain open as to its characteristics and specificities of its issuance. However, before we explore the available design space, we must first establish a more detailed definition of CBDCs and the digital euro.

Defining CBDCs and the digital euro

A Central Bank Digital Currency, as the name suggests, is a form of digital money that is issued by a central bank. For a value medium to be considered a CBDC it must fulfil both requirements simultaneously (Cœuré et al., 2020). By this definition, CBDCs are not an entirely novel concept. Commercial banks in Europe, the US, and most of the developed world are required to hold a minimum amount of cash, as well as deposits with the central bank in the form of reserves. These reserve accounts fulfil the definition of a CBDC presented above, as they are digital representations of value, recorded as a liability of the central bank and an asset for the commercial bank.

The novelty of CBDCs and the digital euro relies on two primary factors, namely the extent to which this digital liability of the central bank is made available to the private sector and the types of technologies and systems to facilitate its implementation and additional innovations. The technological design space and options are explored in-depth later in this report. In terms of CBDC availability, there are two models:

- **Wholesale CBDCs** pertain to the expansion of the reserve model described above to include other legal entities besides commercial banks, whether those are financial institutions or otherwise. In such a model, a CBDC would be reserved for commercial banks and other institutions appointed by the central bank to facilitate payments, remittances, and even the settlement of other financial instruments.

- **Retail CBDCs** are a form of legal tender denominated in the national currency, to fulfil the necessary functions of money, serving as a medium of exchange, store of value, and unit of account, all while constituting a liability of the central bank and asset of the private sector, meaning individuals, households and businesses.

SECTION 1.2: THE CASE FOR CBDCS

While a detailed study of the rationale behind issuing a CBDC is beyond the scope of this report, we will highlight some key issues below: payment efficiency and security, inclusion, financial sovereignty, and the futureproofing of economies.

Payment efficiency and security

Cash remains the preferred medium for exchanges today, with a 2019 ECB study reporting that it was used for 73% of Point-of-sale (POS) transactions and amounted to 48% of the total value of POS payments (down from 78% and 53% respectively from 2017). Its tangible nature, speed, and lack of fees make it convenient for local payments, and the instant transfer of value is favoured by consumers and retailers alike.

However, international and non-cash payments have grown significantly, following the exponential rise of ecommerce. From 2018 to 2019, the aggregate number of electronic payments in the euro area increased by 8% (EC, 2020) to a total of approximately €100 billion with a total value of more than €160 trillion. At the same time, reports from firms such as EY (Bellens, Lloyd and Hamish, 2020) have outlined the changing sentiment towards digital payments. In a relevant survey (Figure 1), top financial leaders from around the world highlighted that, by 2030, mobile payments will dominate the market, followed by biometric and digital asset-enabled payments. Payment system companies already report large increases in the transaction volumes of most online retailers. Indicatively, ACI Worldwide's relevant research (ACI Worldwide, 2020), showcases a 74% increase in transaction volumes for select sectors, while (Adyen, 2021) reports an increase of 30% to 50%.

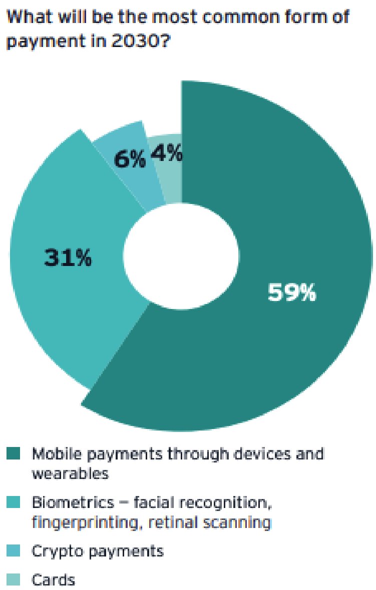

Figure 1 The Future of Payments
Source: (EUBOF)

With the continuous shift from cash to electronic transactions the operational robustness of payments as a whole relies increasingly on credit and debit card networks, e-money providers, and point-of-sale schemes.

Depending on its characteristics and infrastructure, a CBDC can support (Riksbank, 2021) the resilience and efficiency of the payments system by expanding services previously reserved for the commercial banking system to the wider private sector. With a new or improved technological infrastructure (RTGS/DLT) a CBDC can improve resilience. In addition, a CBDC tied to real-life identities could also increase payment security and prevent money laundering and terrorist financing. The level of pseudonymity/anonymity can even be adjusted according to the specifications of the central bank, enabling even a digital alternative to cash, in terms of anonymity.

Inclusion

To the extent that a CBDC can act as medium for pseudonymous/anonymous payments, it could address the consequences of the declining use of cash (Bank of England, 2020a), while at the same time promoting financial inclusion. In a scenario where cash is gradually phased out, it is reasonable to assume that commercial banks and other for-profit institutions might find it fruitless to expand their services to financially excluded groups, such as the unbanked. A substitute of cash is critical to ensure that the most vulnerable parts of our societies are not deprived of access to our economies. Regardless of whether the use of cash declines further, a CBDC could extend financial services to the 1.7 billion unbanked of the world (Asli Demirgüç-Kunt et al., 2017) (26% in Europe, (EC and TNS Opinion & Social., 2016)). To achieve this, some minimum infrastructure would be required, notably Internet, computers and/or smartphones.

Financial Sovereignty

Central banks face two distinct types of risks that have the potential to directly threaten their financial sovereignty. Those relate to monetary policy inefficiencies, and the rising competition from alternatives developed in the private sector.

Since the Great Recession of 2008, central banks have had to resort to rather unconventional methods, such as negative interest rates and quantitative easing. A CBDC can add new weapons to the arsenal of a central bank to facilitate monetary policy and address future crises.

Central banks may also face increased competition from the open blockchain space and the private sector when it comes to the monopoly of money creation. The proliferation of cryptocurrencies, such as Bitcoin and stablecoins, is one such source of possible competition. The emergence of privately-issued digital assets, such as Facebook's Diem (formerly known as Libra) is another. Even competing CBDC deployments by other central banks, may push a central bank to rethink its own position regarding the CBDC phenomenon.

Futureproofing

Depending on its technological infrastructure and availability, a CBDC can also accommodate for trends that will define the future of payments and finance.

Indicatively, the concept of programmable money, largely nurtured in the decentralised space, can allow a CBDC to operate according to complex conditions and rules. This can in theory allow for a greater degree of flexibility, as well as novel features that cannot be implemented otherwise. Programmability of money and interoperability with other digital systems can allow for the convergence between the Internet of Things and value systems, enabling new forms of commerce, such as machine-to-machine (M2M).

SECTION 1.3 THE GLOBAL CBDC COMPETITIVE LANDSCAPE

There are a number of conventional reviews of the state of various CBDC projects, such as the Bank for International Settlements Summary (Auer, Cornelli and Frost, 2020), the Central Bank Digital Currency (CBDC) Tracker, and the CBDC World Map. This section does not intend to duplicate those, particularly as significant updates occur on a weekly, if not daily, basis. But for convenience, here are brief summaries of the major CBDC players, ordered by their current standing as world reserve currencies.

Traditional Players

United States of America

Internal review and discussion efforts for a dollar-based CBDC have been underway for some time. More recently, in August of 2020, The Federal Reserve Bank of Boston announced its collaboration with MIT to research and explore digital currency and build a hypothetical CBDC (Federal Reserve Bank of Boston, 2020; MIT, 2020). After the Federal Reserve's April 2021 police meeting Chairman Jerome Powell cautioned it is "far more important to get it (CBDC) right than it is to do it fast or feel that we need to rush to reach conclusions because other countries are moving ahead.” (Wall Street Journal, 2021). The United States Securities and Exchange commission recently suggested the existence of dollar-based private sector stablecoins was in some sense a counter to China's explicit alliance building. (Wilson, 2021).

European Union

In its October 2020 *Report on a digital euro*, the European Central Bank stated its position on CBDCs, which includes the following key phrasing: "While the Eurosystem would always retain control over the issuance of a digital euro, supervised private intermediaries would be best placed to provide ancillary, user-facing services and to build new business models on its core back-end functionality. A model whereby access to the digital euro is intermediated by the private sector is therefore preferable." (ECB, 2020b). It has also partnered with Bank of Japan in general exploratory efforts which emphasize "Balancing confidentiality and auditability in a distributed ledger environment."

Bank of Japan

The Bank of Japan announced a one-year trial of a digital yen (Ledger Insights, 2021), as follow on to its earlier position paper (Bank of Japan, 2020). There has also been joint work with the ECB as noted earlier.

Bank of England

The Bank issued a position paper in 2020, and in April 2021 organized an exploratory task force. No pilots are underway (Bank of England, 2020a, 2021).

China

Based on information that is publicly available, China's digital yuan is the most well-advanced among leading central banks. This is because of multiple factors. First, its progress in putting the CBDC into public use (Areddy, 2021), efforts to integrate with leading social media offerings such as WeChat, and the breadth of its alliance making with other central banks, as exemplified by its recently announced m-CBDC effort (BIS, 2021), involving SAMA/UAE, Bank of Thailand, and HKMA.

Bank of Canada

Project Jasper is the Canadian banking industry’s CBDC initiative. It was embarked upon in 2017, well before most other central banks were giving CBDCs the attention that they are now giving it. Participants in the project consisted of the Bank of Canada and private banks in Canada and were intended for inter-bank value or money transfer in a somewhat decentralized setting. In one of the initial phases, a private version of Ethereum was utilized. The project then moved to R3’s Corda solution. In this latter phase, some degree of centralization was utilized in the form of a notary node operated by the Bank of Canada. The project utilized digital signatures to verify the authenticity of information. Privacy was maintained among members by participants only having access to transactions that were relevant to them. Private market participants used newly created objects called Digital Depository Receipts (DDR). These were created in exchange for Canadian Dollars. Both are central bank liabilities but DDR was only valid within the scope and systems of Project Jasper (Bank of Canada, 2017, 2019).

Russia

The Bank of Russia has issued a position paper. It specifically calls for a two-tier system: "The selected target model is a two-tier retail model which assumes that the Bank of Russia is both the issuer of digital rubles and the operator of the digital ruble platform. At the same time, financial institutions open electronic wallets for their clients and perform operations over these wallets on the digital ruble platform. Households and businesses will be able to access their digital rubles through any bank where they are serviced." (Bank of Russia, 2021).

Other players with a smaller footprint in terms of their role on the international stage but notable for their activity include:

Hong Kong Monetary Authority

Hong Kong Monetary Authority (HKMA) and Bank of Thailand (BoT) embarked on a collaborative project to enable faster cross-border payments. Initial research by the HKMA focused on retail CBDCs and found that the payment channels were fast enough for their expectations. However, larger transfers of funds between corporations using the correspondent banking model were considerably slower and therefore caused friction in trade. It was found that much of the friction arose from the number of steps involved in transferring funds from one jurisdiction to another. HKMA and the BoT embarked on a proof-of-concept to see if these frictions could be reduced (Bank of Thailand, 2021). They adopted Corda's Enterprise product, R3, for its blockchain solution. Corda's product utilizes a notary system of consensus. In reality, this means that the central banks of both nation states will be involved in the management of the transfer of capital. This shared management is utilized since neither currency has a dominant status over the other. This is unlike the US Dollar where foreign central banks maintain a substantial part of their foreign reserves on accounts at the Federal Reserves. The Federal Reserve does not share access to these "T accounts." Whereas for the HKMA and BoT some semblance of a "shared T account" is necessitated. Consequently, the notary nodes in the solution utilized by both banks have shared management. The HKMA is now proceeding to partner with other nations including the Central Bank of the UAE to further pursue this solution. They are doing so under the auspices of the BIS's new Innovation Hub program.

Project Ubin (Temasek - Monetary Authority of Singapore)

This wholesale (inter-bank) effort is notable for its alliance-making, including with the Bank of Canada (Bank of Canada, 2019; Monetary Authority of Singapore, 2020), and its willingness to "unbundle the digital currency stack" in order to promote broader adoption (*MAS proposes 'unbundling digital currency stack'*, 2021).

Saudi Arabia & UAE

This effort is not a general purpose/retail CBDC - it is a wholesale or commercial bank CBDC. The reason why this is being done is because it is likely there is no centralized balance sheet unlike the Federal Reserve's balance sheet where other central banks hold accounts. This earlier work is in some respects superseded by the recent announcement of coordination with Thailand, HKMA, and the yuan digital currency effort (Kuhn, 2020; BIS, 2021).

Eastern Caribbean Initiative, (DXCD)

Though small in terms of the size of its money supply and traditional market, this effort has the distinct advantage of having already launched. In operation since 31 March 2021, it also integrates multiple different national entities, giving it a practical edge in alliance building (Bharathan, 2021; ECCB, 2021). EU members might also find it interesting historically because it was one of the examples studied as a model for the formation of the Euro itself.

Bahamas

For the sake of historical completeness, the Bahamian Sand Dollar is widely regarded as the first official launch of a CBDC, though its scale is obviously quite small relative to the other initiatives outlined above (Wilson, 2020).

Framing an Evolving Landscape

So how do we frame the competitive landscape for CBDCs in a way that suggests its evolution? We begin with a conventional view, based on the assumption that CBDCs will simply function as linear extensions to the underlying fiat currency.

The conventional view. See Figure 2 (next page).

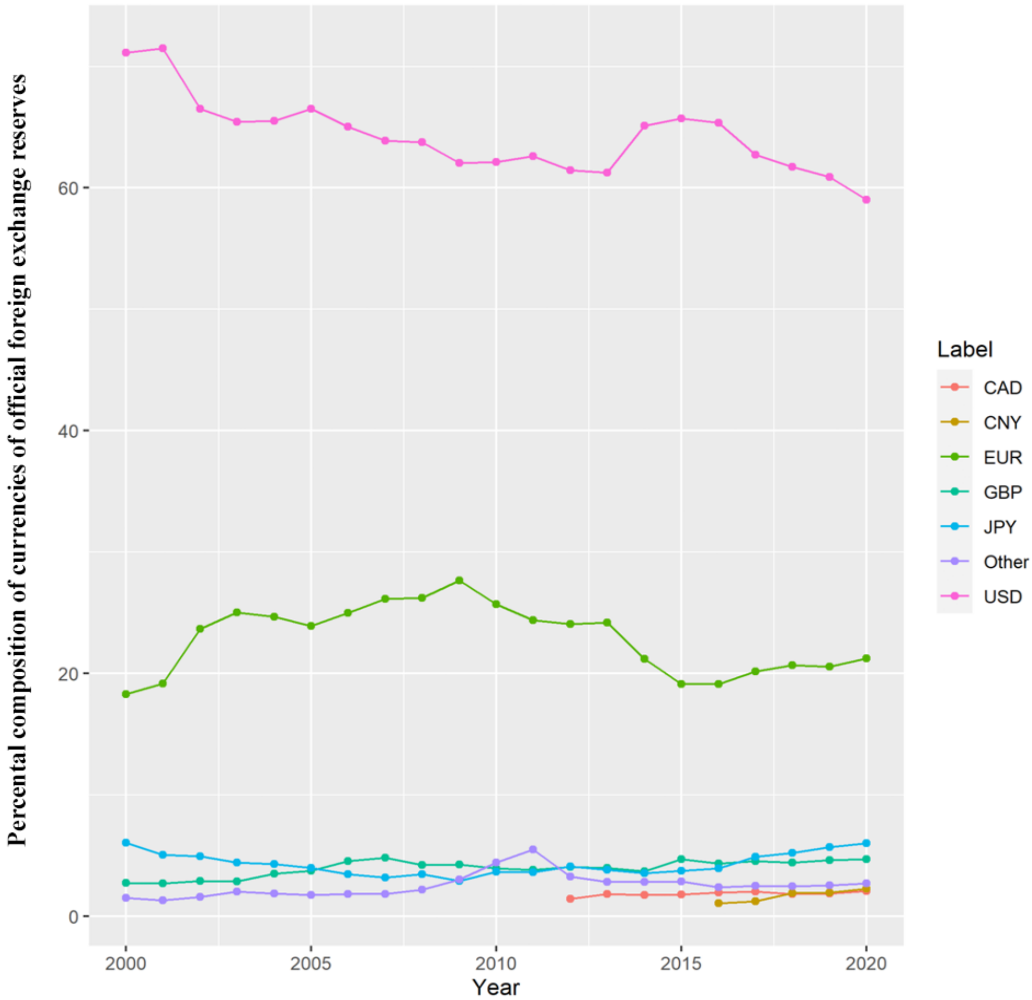

Figure 2 Percental Composition of Currencies of Official Foreign Reserves. Source: [1]

This graph communicates nothing if not stability. Over the past two decades The USD and EUR have held dominant primary and secondary positions, respectively, with a somewhat gradual trend toward tertiary players gaining modest significance.

Figure 3 Indicative Gartner Magic Quadrant **-** payments Source: Gartner (October 2020)

But this may not be a reliable predictor. Rather, let us view the various proposed and current CBDC projects from the perspective of early-stage startup companies entering a rapidly expanding new market. Doing so heightens our sense of the fluid nature of the space. On the one hand, legacy players seek to extend their fiat currencies into a new but adjacent market in the digital realm. On the other hand, entirely new digital startups without the backing of a nation-state are focused on new features to attract users to their currency. One might initially think that the incumbents have an overwhelming advantage of scale and the ability to legislate required

use cases, such as the payment of taxes in the currency, and that of government employees, as well as the ability to regulate the startups. However, what has mattered in the past may matter less in the future. As Jamie Dimon, CEO of JPMorgan Chase, recently wrote: "Fintech's ability to merge social media, use data smartly and integrate with other platforms rapidly (often without the disadvantages of being an actual bank) will help these companies win significant market share" (JPMorgan Chase & Co., 2020). While Mr. Dimon is describing the looming competition between upstart fintech and incumbent banks, it is an apt description of the closely allied ecosystem that exists between fiat currencies, cryptocurrencies and other money-moving rails.

The Gartner Magic Quadrant view and similar two-axis scatter plots of companies have become a staple in assessing emerging markets, particularly for assessing disruption and opportunity. To ease the reader into this kind of thinking an example is included as Figure 3, in this case for meeting solutions, something we are all familiar with due to the pandemic.

In this example, Gartner has made a crucial judgment: namely, that completeness of vision and ability to execute will prove the *two most important dimensions for predicting success* in the space. Those who occupy the upper right quadrant are, in that view, the most likely to be successful over the long term. It should come as no surprise that Zoom, which comes out as a market leader, would use this graph in its marketing materials.

We suggest its use to spur conversation about how the CBDC space may evolve. Of course, the choice of axes is subjective. Chosen well, however, these axes reflect both the correctness of a company's vision as to the determinants of market dominance, and that company's relative strengths. Hence, our graphs have both a subjective (choice of axes) as well as a somewhat more objective (publicly available data on those variables, is subject to interpretation) aspect to them. It is important, therefore, to understand that the graphs we provide below are only two of an infinite number of ways to frame the competitive landscape. Nevertheless, we believe it serves as a helpful starting point to begin a debate about how the EU should consider entering and responding to the threats and opportunities in this space.

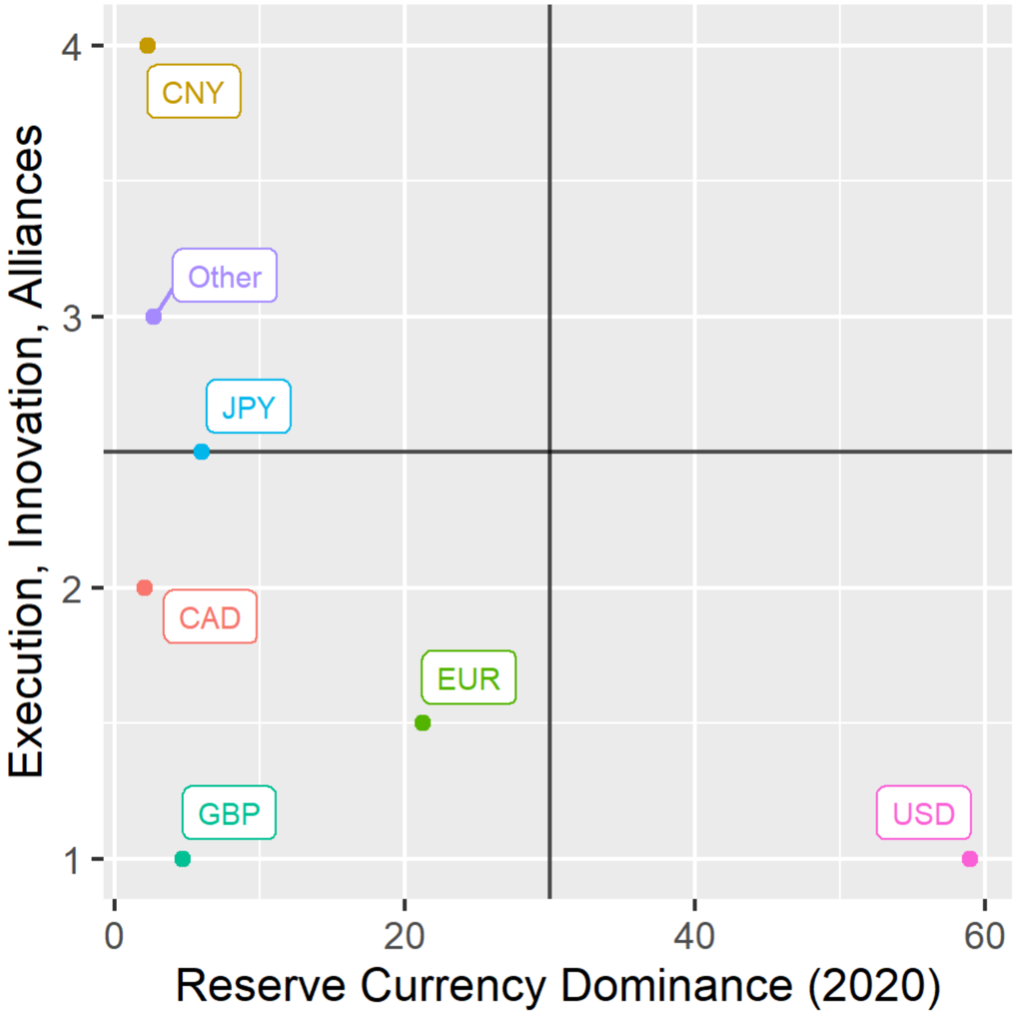

Figure 4 Reserve currency vs. potential for disruption Source:[1]

Figure 4 was constructed to weigh traditional measures of strength against those three characteristics cited earlier by the JPMorgan Chase CEO Jamie Dimon. Namely, social media integration, new value-added features, and network effects. Our assignment of values on this axis is necessarily subjective, but is designed to reflect actual progress rather than inherent ability.

One key aspect of this competitive landscape is to recognize that there are two distinct types of players. Since at least Bretton Woods in 1944, the traditional nation-states have worked both competitively and cooperatively to bolster their currencies as an instrument of monetary policy. Beginning with the creation of the IMF, the World Bank, and coming down to the present with ongoing organizations such as the G7 and the G20, this landscape has evolved within a rather well-defined set of rules, organizations, and meetings among the leading players.

What is unique now is that this universe has some new entrants that are not part of this system. Specifically, **note that some of the projects that will be presented below might not comply with the definition of a CBDC as defined by the report**. For this reason, we call these non-sovereign actors the uninvited guests. This is not intended to be pejorative, but rather a somewhat whimsical way of suggesting that the dynamic is rapidly changing. These new entrants are not nation-states at all but must be taken into account by the incumbents if the fiat currencies wish to prosper. They simply cannot be ignored and excluded from the discussion. We briefly introduce a sampling of non-sovereign actors, representative of a vast array of entrants.

Non-Sovereign Actors

Bitcoin and its ecosystem (e.g. Lightning)

Bitcoin’s appeal starts with the fact that it already exists and has operated for over a decade. This is in contrast to almost every other digital currency which is still ‘vapourware’ and faces an uncertain path to market. Bitcoin has an easily recognizable brand, is already used by hundreds of millions of people and has a vibrant ecosystem of service providers. By virtue of being stateless, Bitcoin has a large “total addressable market.”

Other aspects of the digital currency that some users may find appealing are its algorithmic (and capped) inflation schedule and censorship resistance. Bitcoin may therefore appeal to digital currency users who are wary of the motives by some countries in introducing CBDCs, such as new policy tools enabled by programmability, or economic surveillance.

That said, Bitcoin’s decentralization has its drawbacks. Its throughput is extremely limited and the energy consumption (and environmental impact) of its consensus mechanism is can be considered severe. Having a fixed inflation schedule also makes it vulnerable to severe deleveraging during a crisis, a lesson from other forms of “hard money” that the crypto faithful have yet to learn.

Ethereum

In some ways, Ethereum begins where Bitcoin ends. One of Bitcoin’s core elements is the “transaction out” or TXO. It is the subcomponent within the transaction that is ultimately spent or left alone. Bitcoin Core, the codebase that a node operator might run, comes with a set of operations that one might use to not just merely move TXOs around but to do some more complicated things with it. For example, one might, say, mandate that a TXO, after signing it and moving it another block, can only be spent after a certain number of blocks have transpired. This ability to script allows for some flexibility to users of Bitcoin but the actual possibilities are quite limited, especially when compared with the plethora of high and low-level programming languages that are available at present. To a programmer, it might appear like a limitation. And it is, by design.

This is where Ethereum comes in. It allows for a much richer set of instructions, including simple but dangerous things (in a decentralized setting) like “software loops”. The notion here is that users of Ethereum can set up more complicated instructions that can be activated if someone “kicks off” the instruction set or perhaps because another set of instructions kicked off and so on. With layers and layers of abstraction, one then eventually ends up with smart contracts and decentralized exchanges.

However, this level of complexity comes with a cost. Bitcoin, in a way, gives equal weight to the price (in terms of satoshis/byte) regardless to differing instructions. This could not be allowed in Ethereum as it would allow for, among other things, malicious or harmful (though not intentionally malicious) instructions to execute. Ethereum miners have a limited supply of computing power and just like anything else in the world, to economize for a limited supply of something, a price is set. In this instance, the price of instructions is set using a term called “gas” fees. It is best thought of as the fee to execute instructions. If a sufficient amount of fees (in terms of Ether) is not sent with a set of instructions, then instruction stops - circumscribing the problem of malicious or otherwise harmful instructions.

Ethereum is also different from Bitcoin in other ways. Where Bitcoin evolves slowly but surely, Ethereum changes rapidly and sometimes it is not clear to users whether the changes are positive. A “full node” containing all of Bitcoin’s transaction and block data occupies, at present, less than 400 GB of space. The corresponding node, an “archival node”, occupies over 7TB of space. Finally, where one might not find a figurehead for Bitcoin (although some claim to be), one will find one in the persona of Vitalik Buterin for Ethereum.

Finally, Ethereum plans to be different from Bitcoin in other ways. It wishes to move to a Proof-of-Stake model of consensus as opposed to the Proof-of-work model that exists. It also wishes to use techniques like “sharding” that allows different functions to “shard” into smaller, so to speak, sub-chains while still being able to interact with other sub-chains. The path forward for Ethereum is exciting but also risky. Those two things, of course, go hand in hand.

Stablecoins

Introduced to address some of the volatility of cryptocurrencies while maintaining most if not all of their "desirable" characteristics, stablecoins are tied to a conventional currency, such as the dollar, euro, or a basket of currencies. They purport to offer the stability and familiarity of a traditional currency with the frictionless and programmable promise of cryptocurrencies. There are both decentralized deployments, such as Tether, and privately issued global stablecoins such as Diem and JPM Coin in the works.

Tether is notable as being the largest stablecoin by market cap, and perhaps surprisingly as having the largest daily volume of any cryptocurrency, exceeding even that of Bitcoin and Ethereum (Oluwapelumi, 2021). While it has been the subject of controversy because of suspicions that it did not maintain dollar assets equivalent to its liabilities, there has been recent progress in that area (Kharif, 2021; Tether, 2021).

Diem (formerly known as Libra), which has not launched, is notable for its global ambition. This is largely substantiated by its affiliation with Facebook and the prospect of being able to immediately be accessible to its nearly 3 billion active users, of which nearly 2 billion are daily users (Statista, 2021). And while concerns about the scale of its impact and negative sentiment surrounding Facebook, particularly in US Congress circles, has impeded its progress to date, the potential still remains (Wikipedia, 2021a).

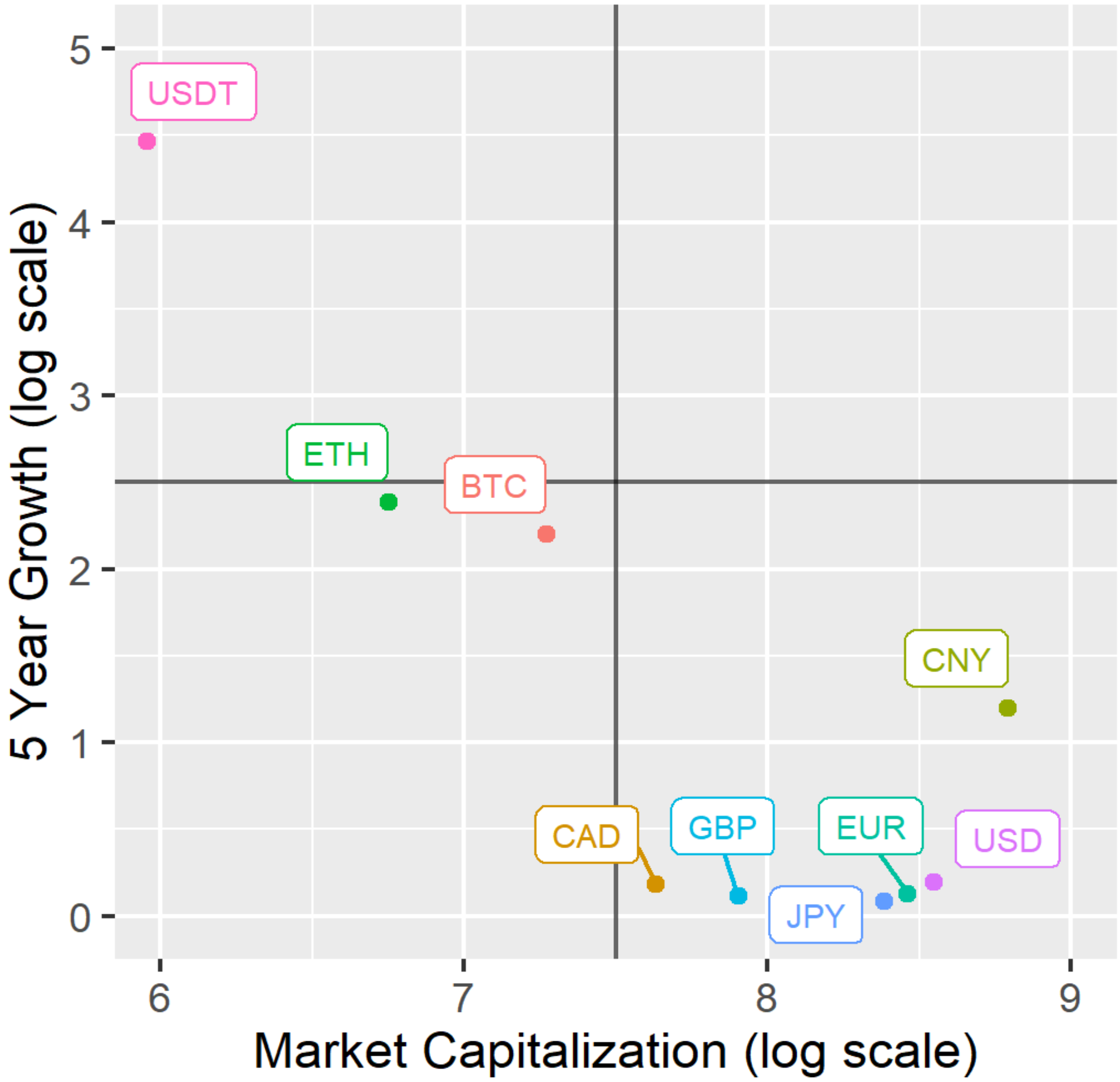

Figure 5 Market cap vs. rate of growth. Sources: [1][2][3]

Our choices for the last graph are likely to be controversial. First, comparing the market cap of a cryptocurrency such as Bitcoin, with the market cap of the euro can certainly be criticized as comparing apples to oranges. The trading volume of cryptocurrencies is miniscule compared to traditional currencies, and so some sort of velocity-adjusted market cap might be more appropriate. Similarly, the five-year growth rates of fiat currencies are largely a reflection of the growth of their underlying economies. Leading cryptocurrency growth rates, in comparison, are astronomical over the past five years, with Tether an outlier even among outliers. But we can think of no other way to compensate for the tendency among incumbents, in any industry, to neglect exponential growth from small competitors until it is too late. In that respect, we judge the ability of these cryptocurrencies to enter the upper right quadrant of the graph as well-depicted.

A Framework for Action

Central banks find themselves in a classic innovator's dilemma situation (Wikipedia, 2021b).They must maintain their core user base against encroachment, both from other central banks' efforts to expand their influence globally, and from non-sovereign actors. They have the advantage of incumbency and a large customer base. Yet the stupendous exponential growth of alternative currencies and the relentless innovation, tie-ins to social media, and efforts to form alliances among less-established players willing to take risks is not to be discounted.

Consider, by way of historical illustration, the case of Minitel (Minitel). Throughout the 1990s, Minitel, France Telecom's offering, was a force to be reckoned with in the nascent e-commerce space. Backed by the de facto imprimatur of the federal government, its end-to-end hardware/software solution included secure e-commerce, connections to tens of thousands of businesses, and an essentially captive customer base of several million users effectively imposed by fiat. Combined with its exponential growth, it seemed to many to have an unassailable lead over the upstart, open-source Internet. After all, the Internet was nothing more than an overgrown academic experiment, with no security, no official backing, and skepticism from the business community.

Minitel made multiple efforts to expand internationally, drawing on the formidable strength of its success in its home market, coordinating with sister organizations to France Telecom in other nations. And yet the Internet's uncoordinated, decentralized growth rapidly dwarfed the Minitel effort, first overseas, and then within France itself. Its last territorial redoubt seems to have been, at least symbolically, a group of dairy farmers who lacked access to broadband in remote areas of the country (ABC, 2012).

Today, Minitel is but a footnote in history, completely overwhelmed by the Internet/ World-Wide-Web. Such is the sobering story that should serve as a cautionary tale as various nations extend their fiat currencies into a CBDC. Again, our point is certainly not to disparage the Minitel effort. In fact, the project is well-known precisely because it did so many things right. But it did not win out. Similarly, while the euro brings many strengths to bear in moving into CBDCs, we must at least consider the fact that it not just fails to expand its influence, but finds itself in defensive retreat even within its own borders. Competition could come from other fiat currencies or from or non-sovereign actors, who end up evolving more useful features or create dominating network effects accelerated by strategic alliances, all at exponential rates that shrink the timeframe for appropriate response.

How then, to respond? It is not our place to offer specific advice, but a framework for response is certainly possible. First, do no harm. It may go without saying, but we will say it anyway: the stability of the financial system within the EU is paramount. Continuing to do what central banks to date have done well, despite challenges, is overwhelmingly the first priority. That being said, a CBDC creates the possibility of an innovative ecosystem that can be built on top of a stable, well-managed currency. Here one should look to cultivate relationships with the private sector beyond traditional banks to find new ways of creating value. Consulting with companies that have successfully launched CBDCs, even if on a smaller scale, is also an obvious accelerant to one's own activities. In addition, alliances become important, as network effects can extend well beyond traditional geographies. These ecosystem-building responses require a skillset that is altogether different from one optimized to maintain quiet stability, and should be dealt with structurally to avoid the crux of the innovator's dilemma (Walk, 2021).

One can raise concern without being alarmist. CBDCs offer an opportunity to increase the reach of monetary policy, to create a platform on which value-adding applications can be built, and the ability to increase the reach of the euro beyond its native boundaries. But the pace of innovation by other actors, both nation-backed and private decentralized efforts, is relentless. And these other players will take no quarter. The days of well-agreed territorial boundaries for currency usage and polite coordination among nation-states is ending, superseded by a global race to redefine the medium of exchange and the future of money. Leaders would do well to take note, as the race for the upper right quadrant is well underway.

SECTION 1.4: THE DIGITAL EURO TIMELINE

The timeline for a digital euro begins in a joint statement by the European Council and the European Commission on stablecoins in late 2019. The press release (EC, 2019) noted that the then-recent rise of stablecoins underlined the significance of addressing consumer needs for fast, cost-effective, and efficient payments and cross-border remittances. The possibility of a CBDC to address these was also mentioned.

Christine Lagarde, president of the ECB, has laid the foundations for a digital euro in her speech at the Deutsche Bundesbank conference in September of 2020 (ECB, 2020a). Ms. Lagarde highlighted the changing consumer sentiment towards digitalization, e-commerce, and electronic payments, further accelerated by the COVID-19 pandemic, along with the rising competition to dominate payments on a global level and Europe's disadvantaged position in the race. The issues of private money with weak connections to a sovereign counterpart, and mobile payments controlled by private firms, were also emphasized as a potential threat to financial sovereignty. A state-backed digital currency, widely trusted by the general public, was promoted as an option for managing the risks of this digital transition while maintaining trust in the existing payments system.

At the same time, the European Commission was adopting the Digital finance package to ensure competitiveness and stability in the Fintech sector. As part of that package, the Markets in Crypto-Assets Regulation addressed cryptocurrencies that fell beyond the scope of existing European legislation and introduced uniform rules for the treatment of stablecoins, leaving room for a pan-European sovereign deployment as a viable alternative. A month later, in October 2020, the ECB published the report on a digital euro (ECB, 2020b).To date, this report constitutes the most comprehensive analysis of the motives behind a European CBDC and its desirable characteristics.

The analysis was released in conjunction with a request for public consultation on the characteristics of the digital euro. Following record participation of more than 8,000 citizens and institutions, the results went public in April 2021. The overwhelming majority of respondents promoted privacy and security as the two most desirable features of a digital euro, as collectively they were highlighted in more than 60% of responses. Accessibility throughout the euro area, no additional costs tied to the use of the new euro, and offline usability were also promoted as close runner-ups. The importance of intermediaries as facilitators of innovative services, smartphones for secure payments, and holding limits or other techniques to manage the amount of digital euro in circulation, were also highlighted. The majority of respondents were men (87%), citizens of Germany (47%), Italy (15%), and France (11%), with the remaining Member States accounting for between 1% and 5% of the total.

Figure 6 Digital euro timeline. Source: (EUBOF)

Chapter 2: The Digital Euro Design Space

SECTION 2.1: CORE PRINCIPLES, SCENARIO-SPECIFIC AND GENERAL REQUIREMENTS

The “Report on a digital euro” was published by the European Central Bank in October 2020. In it, the ECB, while acknowledging that “it is still too early to commit to a specific design”, formulates a guidebook of desirable characteristics for the digital euro. In this section, we examine these characteristics across three categories: core principles, scenario-specific requirements and general requirements.

Core principles

The report lists 5 core principles that can be thought of as fundamental requirements for a digital euro, rooted in the rules and processes that underpin the Eurozone. A digital euro must (1) be convertible at par with the regular euro, and (2) controlled by the Eurosystem. Additionally, it should also (3) be available on equal terms in countries of the Eurozone, (4) through appointed third parties, so as not to displace private solutions. Finally, (5) it must remain a trusted solution by end-consumers.

Scenario-Specific Requirements

Furthermore, the report identifies seven specific scenarios that may require the issuance of a digital euro. These include: (1) support of digitalization; (2) address the declining use of cash; (3) combat the risks of private money creation; (4) expand the monetary toolbox; (5) improve payment system resilience; (6) strengthen the relevance and international utility of the euro; (7a) facilitate cost efficiency, and (7b) environmental sustainability.

1. More specifically, to support digitalization and increase usability, efficiency, and decrease the cost of payments, a digital euro should borrow from state-of-the-art technologies developed in the private sector, and be made available via standardised solutions throughout the euro area.

2. To further financial inclusion and counterbalance the declining use of cash, it is also crucial that a European CBDC exhibits cash-like features, such as adequate privacy, security features, and no fees attached to its use. This is to ensure that underprivileged and vulnerable individuals and groups are not excluded from the economy.

3. Additionally, a digital euro should remain attractive and competitive when compared to solutions deployed by private and foreign actors. By doing so will protect the global place of the euro and limit the influence of money that is removed from the protection and guarantees of sovereign deployments.

4. A European CBDC also provides new ways to drive the economy towards beneficial outcomes, by offering new monetary policy tools, and altering the transmission mechanism of existing systems.

5. Additionally, to strengthen payment resilience, a digital euro can also serve as a back-up system and contingency mechanism for electronic retail payments in the case of a cyber incident, natural disaster, or pandemic, thus increasing the resiliency of the payment systems and mitigate the associated risks. The COVID-19 pandemic in particular showcased the need for resilience in digital payments. A European CBDC could offer a parallel infrastructure to other payment solutions to overcome extreme events.

6. A digital euro should also strengthen the international presence and utility of the euro through its accessibility beyond the euro area. In this context, a digital euro would support the euro's global role, while remaining consistent with the objectives of the Eurosystem.

7. Finally, among the scenarios discussed in the ECB's report on a digital euro, is using a European CBDC as a vehicle for improving the cost efficiency and ecological footprint of the monetary and payment systems.

General requirements

General requirements refer to desirable characteristics that ensure the relevance, prominence and interfacing of a digital euro with existing systems and processes. The report identifies 5 such requirements, namely, (1) the ability to control the amount of digital euro in circulation; (2) the need to coexist (cooperate) with other market participants; (3) to comply with regulatory standards; (4) the requirement of safety and efficiency in the fulfilment of the Eurosystem's goals; (5) its accessibility throughout the euro area through standardized and interoperable solutions; (6) use outside of the euro area; and finally (7) cyber resilience.

1. To ensure the smooth operation of the existing financial system, and the non-disintermediation of the commercial banking sector and other related actors, a digital euro should be appealing as a medium of exchange, but designed to mitigate bank runs and other similar disruptive events that may result in large capital shifts away from private solutions.

2. To facilitate for synergies with other market participants, a European CBDC should also be designed and introduced following the acceptable standards and best practices in IT. Moreover, it should be available equally across all the euro area countries via supervised intermediaries that leverage existing business networks to ensure cost efficiency.

3. Additionally, a digital euro should comply with existing regulatory frameworks and Europe-wide regulations. Despite central bank liabilities being subject to regulation and oversight, the Eurosystem should strive to achieve compliance with existing regulatory standards, including those from the payments area.

4. In addition to safety, the options for a European CBDC should be produced from a cost-benefit analysis to ensure the efficiency and economic viability of the project. To facilitate additional cost-savings, non-core services of digital euro should be left to supervised private entities.

5. To facilitate accessibility throughout the euro area, a digital euro should be made available through standardized front-end solutions in all euro area countries, while at the same time achieving interoperability with existing public and private payment solutions, including cash, and be accessible even by those currently financially excluded.

6. Specific provisions should be made for the conditional use and access of digital euro by non-euro area residents, that also ensure that volatile capital flows or exchange rates are within certain limits.

7. Finally, the digital nature of this new euro also necessitates its resilience to cyberattacks. As such, its potential deployment should be through resilient and technologically sound channels to ensure fast recovery times, security and data integrity.

SECTION 2.2: DESIGN OPTIONS

Having explored the core principles, scenario-specific requirements and general requirements of a digital euro, the next step is to outline the available design space and options.

Our analysis draws from a popular study by the Bank of International Settlements titled "The technology of retail central bank digital currency" (Auer and Böhme , 2020). The paper translates the needs of consumers to corresponding design choices. The authors identify four areas of fundamental design choices, namely, (1) "The Architecture", meaning the nature of claims of a CBDC and the corresponding role of the central bank, (2) "The Infrastructure", or the dichotomy between a conventional (RTGS) or novel DLT infrastructure; (3) "The Access Technology" or choice between an account or token-based method for verifying transactions and (4) "The Interlinkages", meaning whether a CBDC is for wholesale or retail use. Naturally, by drawing from this analysis, we also acknowledge pre-existing as well as follow-up research.

In general, and in terms of the **management of a CBDC**, reports from academia and industry are in broad agreement that this could be handled entirely by a central bank or through a collaborative effort that involves the central bank, commercial banks, and even other financial institutions, with accompanying implications for the nature of claims. Most relevant reports also showcase the **debate** of an account versus token-based access method for CBDCs. Additionally, the dichotomy of real-time gross settlement versus a novel blockchain or distributed ledger technology (DTL) as the **underlying infrastructure** is another prevalent and recurring theme in literature. Finally, other satellite considerations exist, such as the nature and function of digital wallets to facilitate the transfer of CBDCs, however, these can easily be incorporated in one of the previous areas.

From the above, we can denote that by wide consensus, the most notable considerations when it comes to the design space of CBDCs, and in turn a digital euro, necessarily include **the access method** for authenticating and verifying ownership and authorizing changes, **the ledger infrastructure** for recording transactions and state transitions, and finally, **the management** of the technology stack and accompanying liabilities. For this report we will not consider the option of a wholesale CBDC, as in the words of the ECB's president Cristine Lagarde "Digital wholesale money is not new, as banks have been able to access central bank 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" (ECB, 2020a). Simply put, an analysis of a potentail retail digital euro, is more compelling, not only academically, but also pragmatically. Nevertheless, segments of the present apply to a wholesale digital euro too.

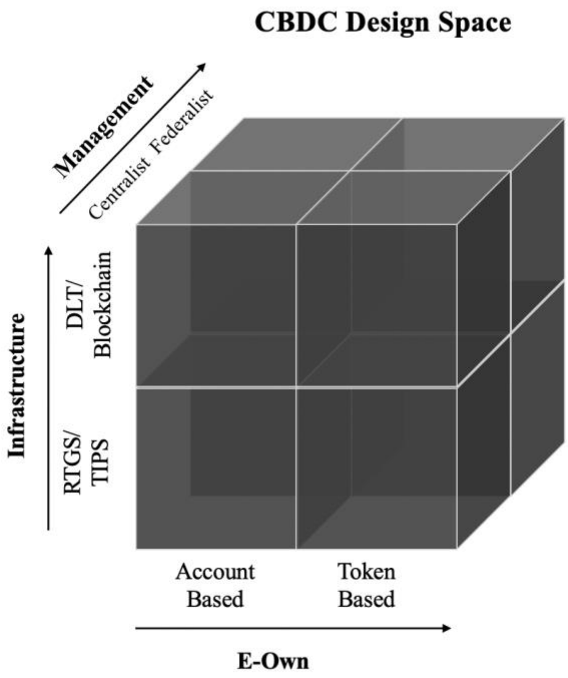

Figure 7 CBDC Design Space. Source: (EUBOF)

Evidence of Ownership – An account-based approach

We begin by examining how ownership of value and authorisation of transactions is proven and verified. In the case of cash, this is often overlooked as apparent. Central banks, as issuers of currency, do not record information on ownership or transfers. The simple possession of cash, whether that is euro, dollars, or otherwise, serves as sufficient proof of ownership; and handing over said cash, as sufficient transaction authorisation. However, the digital nature of a European CBDC necessitates digital solutions. This means that it must rely on either an account or token-based system for ownership and transaction authorisation.

Modern economies largely operate on account-based systems, in which ownership of money is recorded in databases and tied to strong individual identities. The most popular example of the are bank accounts. Account identities are then carried throughout the entire payments system for proving ownership of funds and authorising transactions, giving birth to the notion of "I am, therefore I own". A digital euro utilising accounts could operate almost identically to commercial bank accounts and offer familiar features such as online money transfers and POS payments with plastic.

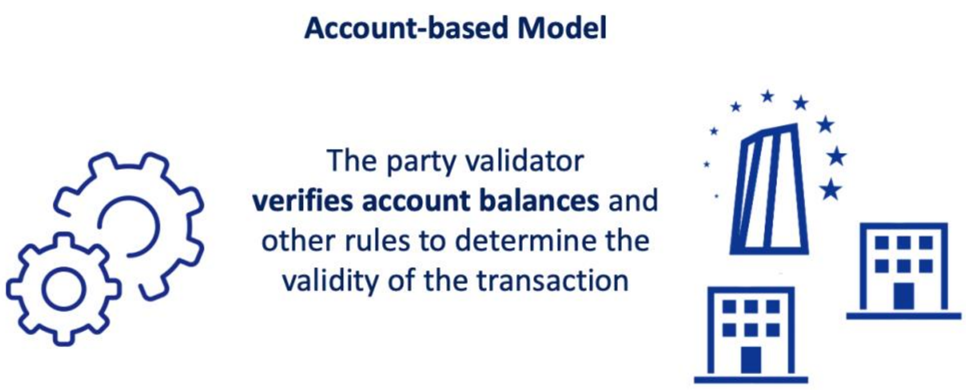

Figure 8 Account-based model Source: (EUBOF)

Figure 9 Accounts: I am, therefore I own Source: (Auer and Böhme, 2020)

This approach is generally favoured for its relative simplicity, proven reliability, and interoperability with the existing payment systems. Additionally, it may facilitate a smooth and cost-effective transition to a digital euro, as commercial and central banks already operate on an account-based system. However, it does little to further financial inclusion and ensure anonymous and private digital transactions, although counter-solutions have been proposed.

Evidence of Ownership – A token-based approach

The second option is what is commonly referred to as a token-based CBDC, a concept largely nurtured and popularised in the open blockchain space and an attempt to replicate much of the functionality and features of cash. In a token-based system, ownership of an asset, in our case the digital euro, is not necessarily recorded in a database and tied to identity. A token-based system relies on the individual person or entity to perform a set action, such as exhibit knowledge of a certain value. In the case of Bitcoin for example this action pertains to producing a digital signature (Auer and Böhme , 2020). This is achieved through a pair of public and private keys that are used to produce and verify digital signatures, thus acting like electronic fingerprints. Users sign transactions using their private key which is to be kept secret. The validity of the transaction is confirmed when the public key is compared to the signature generated by the private key. This allows anyone to verify the validity of a signature, and thus transaction as long as they have access to the public key and signature. Ownership of the private key enables full control of the underlying asset, similar to how ownership of cash enables its full control. In that sense, a token-based digital euro could be considered a bearer instrument, similar to cash but digital, requiring no identity ties. This has given birth to the notion of "I know/possess therefore I own". Token-based systems can either operate in a self-custodian manner, where end-users are responsible for storing and managing their private keys, or through third party custodians, such as commercial banks and other Payment Service Providers (PSPs). Intermediate solutions are possible with multisignature (multisig) deployments.

Naturally, due to their reliance on cryptographic proofs instead of identities, token-based systems are favoured for their privacy and accessibility and relative cash-likeness. However, besides the costs of adopting or

developing such a token-based infrastructure for a digital euro, open questions remain (that are addressed later in the present document) about the implications of such a system for end-user fund management, know your customer requirements, anti-money laundering, etc.

Figure 10 Token-based model Source: (EUBOF)

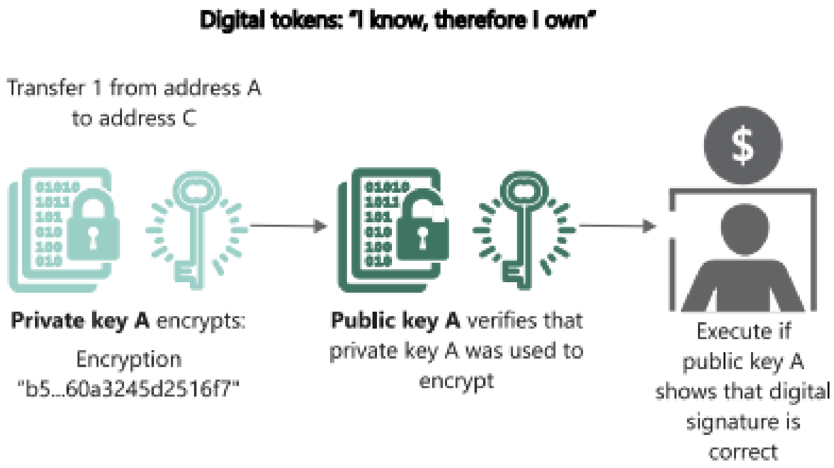

Figure 11 Digital tokens: "I know, therefore I am" Source: (Auer and Böhme , 2020)

Evidence of Ownership - the Account vs Token debate

While seemingly in stark contrast to each other, these categories do share some grey areas and the categorization largely depends on the broader or narrower definition of the two. Indicatively, (Milne, 2018) categorically argues that cryptocurrencies can be characterised as account-based systems, while (Birch, 2018) establishes convertibility into fiat currency, commodities or other assets as a prerequisite of token money. If, for argument's sake, one considers Bitcoin and evaluates it against this dichotomy, they have to conclude that Bitcoin may fit in both categories. Firstly, Bitcoin is account-based, since every user has to create a digital wallet, a type of an account, that supports the use of the Bitcoin blockchain network, and which is only accessible to those that know the private key. To some extent, the private key knowledge can be a proxy for identity verification. Secondly, Bitcoin may also fall into the category of token-based money, because when paying with bitcoins, the network's validation process examines the transacting history of the token and ensures that it has not been spent more than once (Garrat et al., 2020). According to the Bank of England and Riksbank, the design choice between token and account-based systems is not a crucial one, since also a token-based system may be connected to various identity-verification methods on par with the account-based system (Bank of England, 2020) (Claussen, Armelius and Hull, 2021). However, it has to be noted that some authors perceive the identity very narrowly as in referring to the personal identity of the account-holder, and this include bitcoin directly in the category of token-based currencies (see for instance Auer and Böhme, 2020). Furthermore, in trusted systems that necessitate some form of real-world identity tie for asset holders, even if conditional, token-based systems do not offer material benefits over accounts and *vice versa*.

As for the use of the term "E-Own"

Most relevant literature utilises the terms "Proof of Ownership", "Proof of Access" and similar patterns to describe this dichotomy of account-based versus token-based infrastructures. This naming scheme is largely borrowed from the open blockchain space that operates under the principle of "Code is Law" and ultimate finality. In a perfect "Code is Law" world the signing of a transaction with a private key would be definitive proof of ownership and authorisation for a blockchain network that is agnostic as to intentions and other arbitrary non-hardcoded rules (such as those of the legal system). That is regardless of whether this action was intended or unintended or even unlawful. This approach is cherished by some and criticised by others. However, we can assume with a great amount of certainty that the above will not be true for a European CBDC. Instead, a digital euro will operate under the principle of "law is law" instead of "code is law", with transactions as a result of unauthorized access, fraud, or technical malfunctions, open to dispute in court or otherwise. For that reason, we propose the term Evidence of Ownership (E-Own) instead of Proof of Ownership/Access to represent the account versus token dichotomy. That is, to denote the disputable nature of the claim on a digital euro and represent the material difference between centralised and decentralised systems.

Ledger Infrastructure – RTGS/TIPS

Concerning the ledger infrastructure to record transactions and state transitions for a digital euro, the two primary options available to regulators are Europe's Real Time Gross Settlement System (RTGS), or TIPS, either in its current state or modified, and that of a novel blockchain or Distributed Ledger Technology (DLT) infrastructure.

Considering the history of RTGS systems in Europe, TIPS, introduced in 2018, is a relatively new development. Despite that, it is largely based on the time-tested TARGET2 established in the mid-2000s. Employing existing technologies and infrastructures comes with a plethora of benefits. These relate to their proven resilience, interfacing with existing systems, established workflows, and compliance with legal frameworks. The aforementioned benefits ultimately result in cost/time savings and a collection of familiar features and trade-offs.

TIPS has proven (Visco, 2020) a safe, stable, scalable, and user-accepted real-time payments and processing environment. The settlement of transactions between bank accounts happens almost instantly, with 99 per cent settling in under 5 seconds. TIPS's high processing capacity means that it can handle more than 40 million payments per day, at a rate of 500 transactions per second with a peak of 2,000. It operates 24/7/365 and does not necessitate downtime or maintenance windows, due to self-healing capabilities. Even in the event of a disaster, its recovery time is set to not exceed 15 seconds. This autonomous and redundant operation ultimately results in low running and maintenance costs. Finally, as a public service, TIPS does not compete, but rather interoperates and complements market solutions by private actors, adopting a neutral approach with regard to different technology standards adopted by the market.

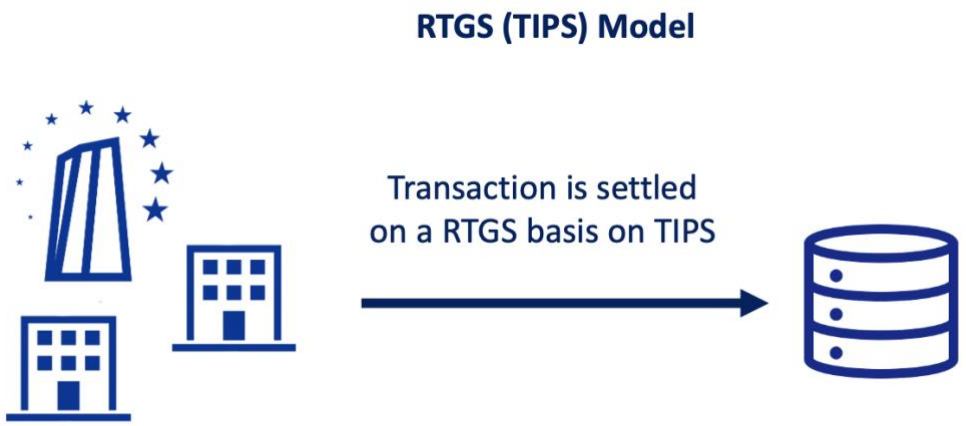

Figure 12 RTGS (TIPS) Model Source: (EUBOF)

However, despite its wide availability in 56 countries, and its ability to settle transactions in foreign currency, TIPS is strictly limited to institutions participating in its network. Moreover, it lacks interoperable bridges with solutions deployed in the open blockchain space, thus necessitating the emergence of sub-optimal solutions such as privately issued and euro-pegged stablecoins. Finally, while a TIPS infrastructure for a digital euro makes intuitive sense in an account-based E-Own scheme, a token-based scenario may necessitate modifications to TIPS to accommodate for the differences in data structures.

Ledger Infrastructure – Blockchain/DLT

The alternative digital euro ledger option available to regulators is that of a blockchain/DLT infrastructure. While the two terms are not identical, in the sense that blockchain is a type of DLT with special features, we will use them interchangeably in the present. The explosive growth of cryptocurrencies and surrounding hype has falsely promoted blockchains as a cure-all. In practice most of the cherished properties associated with cryptocurrencies and other blockchain-based systems are a result of adjacent innovations. These include protocol rules to dictate the properties and monetary attributes of cryptocurrencies, novel mechanisms for achieving distributed consensus without the need for centralised control, and the use of cryptography to achieve security without the need of physical or legal force. Additionally, smart contracts, decentralised applications, as well as abutting solutions (layer 2) are responsible for much of the functionality found in such systems. In casual use, the term blockchain refers to this collection of technologies. However, in isolation, blockchains are but a component of this stack that serves as a ledger to record transactions and state transitions.

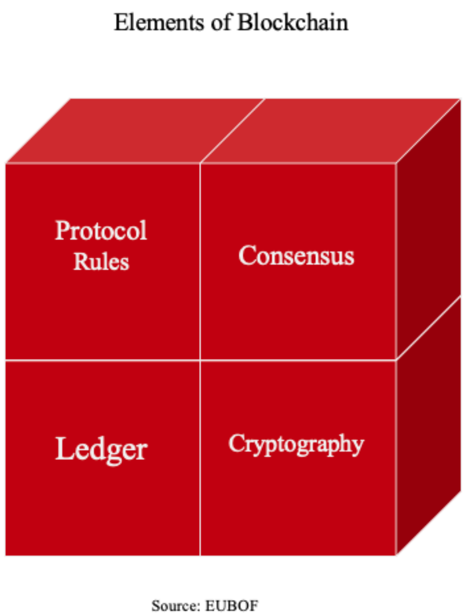

Figure 13 Elements of blockchain

Source: (EUBOF)

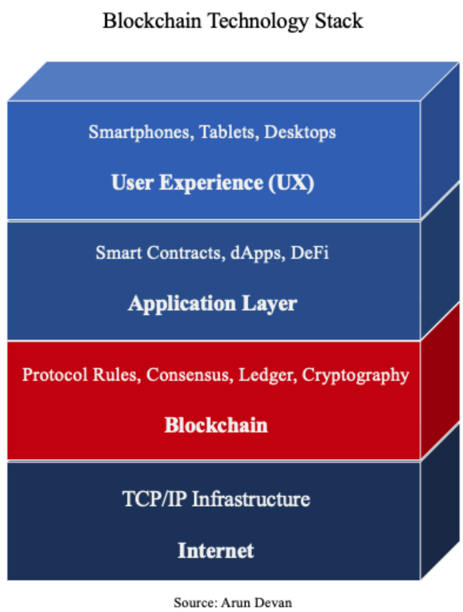

Figure 14 Blockchain technology stack

Source: (EUBOF)

Given the confusion that surrounds the term 'blockchain', we feel it is necessary to provide a concrete definition to specify its use, at least in the present context. Contrary to popular belief, the concept of DLT/blockchain technology was not introduced with Bitcoin in 2008. Instead, a similar scheme was proposed in the 1980s by David Chaum, and later by Stuart Haber and Scott Stornetta. In fact, out of the 8 works cited in the Bitcoin whitepaper, 3 were papers of Haber and Stornetta.

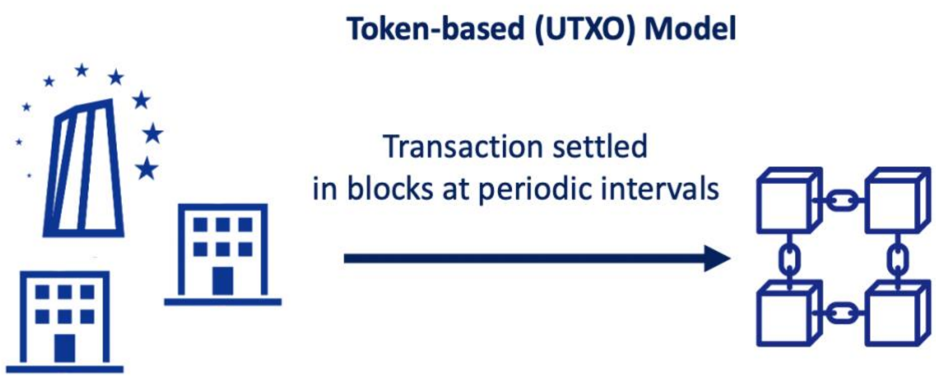

Figure 15 Token-based (UTXO) Model Source: (EUBOF)

Blockchains are a type of DLT. They are append-only data structures organised in data sets called blocks. Each block of data refences the previous by including its digital fingerprint in the form of a hash as part of its data set. This creates a chain of cryptographically linked blocks that conveys sequence in a tamper-proof way, as altering the data of one data set would modify all subsequent hashes. Those blocks are distributed in a peer-to-peer network in a way that each participant (node) can verify the validity of information on their own. Updating this data set or ledger according to set rules requires network participants to reach distributed consensus on the true state of the network. In decentralised systems, such as Bitcoin and Ethereum, this network is comprised of mutually distrusting participants that are economically incentivised to reach consensus. Blockchains and consensus mechanisms were initially devised as a way to enforce rules, such as the prevention of double-spend transactions, without the need of a trusted third party. In fact, according to Satoshi Nakamoto, the pseudonymous creator of Bitcoin, “the main benefits are lost if a trusted third party is still required” (Nakamoto, 2008).

As demonstrated consensus mechanisms are an integral part of blockchains, as without them they are little more than a data structure. Over the years an abundance of alternative mechanisms have been proposed. A key distinction is that permissioned systems that reserve participation for appointed, vetted and known entities operate in comparably less adversary environments. As a result, they can rely on the accountability of their nodes node for the validity of information. A plethora of consensus mechanisms that rely on trusted entities have been proposed over the past decades. This sentiment is encompassed by a concept known as Proof of Authority (PoA). The term was introduced in 2015 by co-founder and former CTO of Ethereum Gavin Wood (Wood, 2015). PoA systems rely on a small set of trusted and reputable entities to act as transaction validators and update the ledger. In the case of a European CBDC the list of validators can be adjusted to include the Central Bank, national banks of European Member States, commercial banks and even other stakeholders from the private sector.

PoA blockchains abolish many of the principles upheld by their decentralised counterparts including transparency, openness and immutability in favour of efficiency, speed, scalability, flexibility, control, and reversibility. A digital euro deployed on such PoA DLT/blockchain system would facilitate the adoption of either an account/balance-based or token-based system that operates with UTXOs, leave room for a more decentralised governance scheme, and make interoperability with blockchain deployments easier, due to a similar structure. Additionally, and depending on the degree that open source blockchain design influences the ledger infrastructure of a digital euro, code and applications developed for the open blockchain space could be run natively in a digital euro, thus achieving programmability of money.

In terms of resilience a DLT/blockchain digital euro is not necessarily better than a TIPS-based infrastructure, and vice versa. Currently TIPS uses a geographically distributed architecture in all of its layers, similar to that employed by blockchains. However, in contrast to decentralised PoW blockchains that necessarily employ costly consensus algorithms to verify transactions, the recognition and guarantee of the transactions comes from the trust provided by the Eurosystem, as would be the case in a PoA system.

The main argument against the implementation of a DLT/blockchain infrastructure relates to the overhead costs of its deployment, the accompanying adjustments of the regulatory framework, non-interoperability with existing payment infrastructure especially when compared to TIPS, versus the added benefits that it may offer. A blockchain infrastructure, depending on its characteristics could facilitate interoperability with other blockchains in the decentralised space.

Management Scheme – Centralist/Direct

When it comes to the management of the infrastructure, whether that is based on TIPS or blockchain, and operates in an account-based or token-based manner, the general consensus of the academic community is that this can be handled either by the Central Bank in isolation, or in collaboration with other commercial banks and Payment Service Providers (PSPs). We coin the term "Centralist" and "Federalist" to respectively describe a management scheme which involves the Central Bank alone, or in collaboration with other entities. There are two primary options, namely the Centralist, or direct, and Federalist, which can be either indirect or hybrid, all with accompanying implications for the nature of claims.

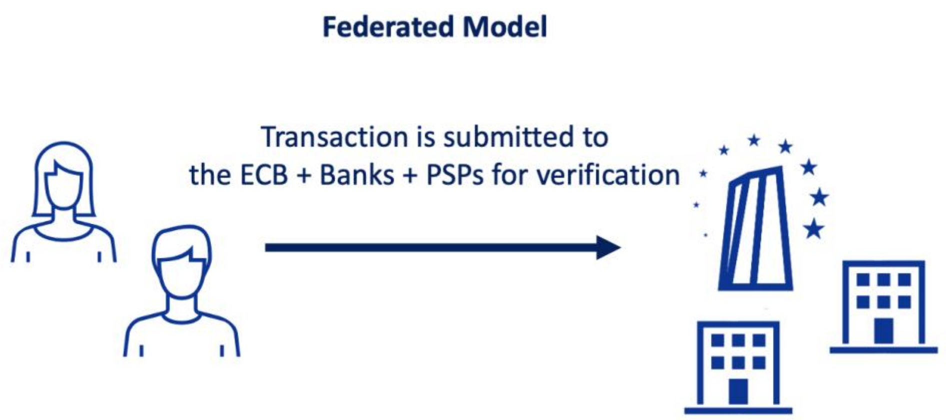

Figure 16 Federated Model Source: (EUBOF)

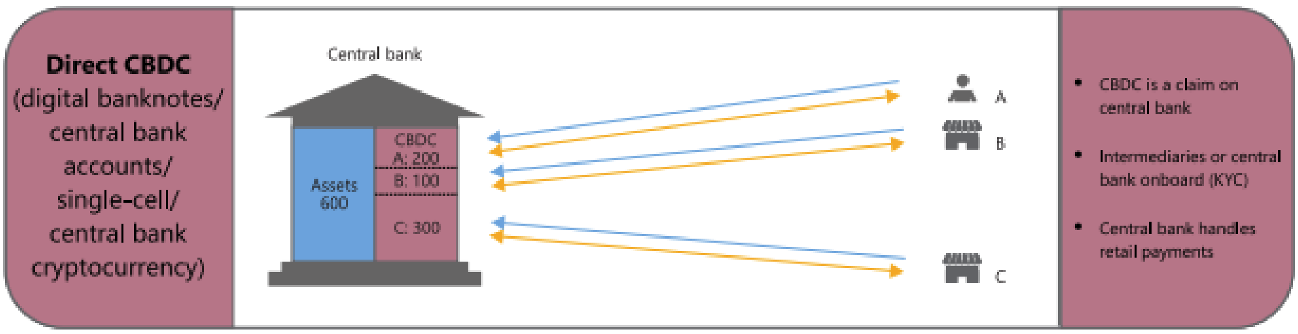

Figure 17 Direct CBDC Source: (Auer and Böhme, 2020)

Management Scheme – Centralist/Direct

Perhaps the most intuitive management structure is that of a Centralist/direct digital euro. In a direct model, the ECB would be responsible for managing the critical components of the technology stack, including holding accounts or token metadata of end-users, and for updating said TIPS or blockchain ledger. In such a system the digital euro would be a liability of the Central bank and asset of the private sector. As such, end-users would enjoy the protection, guarantees, and lack of credit risk that central bank solutions provide.

Despite its attractive simplicity, a Centralist solution, with the Central Bank being the epicentre, disintermediates primary stakeholders of our economies, including but not limited to commercial banks, credit card networks and other private e-money and payment solution providers. Simply put, if the Central Bank is to be responsible for the digital euro and supporting infrastructure, those stakeholders will either have to drastically alter their operations and profit streams, or wither to obscurity. A direct architecture could perhaps leave room for commercial banks and other stakeholders from the private or public sector to handle satellite functions and forms of due diligence, such as KYC/AML. In any other case the Central Bank would have to expand its operations substantially to accommodate its new responsibilities and develop the necessary expertise to manage retail customer relationships (Bech, Hancock, Rice and Wadsworth). Such radical changes come with significant financial costs, which relate to the development of relevant infrastructure and training as well as regulatory overhead. Along the way, and until such new systems are streamlined, the benefits of security, efficiency, reliability, and direct relationship that users enjoy through commercial banks and other institutions may be compromised. Solutions to counterbalance the effects of this shift, such as the central banks lending CBDC deposits to commercial banks, are being proposed. However, their effectiveness is still under debate.

Management Scheme – Federalist/Indirect & Hybrid

When it comes to managing the infrastructure of a digital euro collaboratively, there are two primary approaches suggested by the relevant literature.

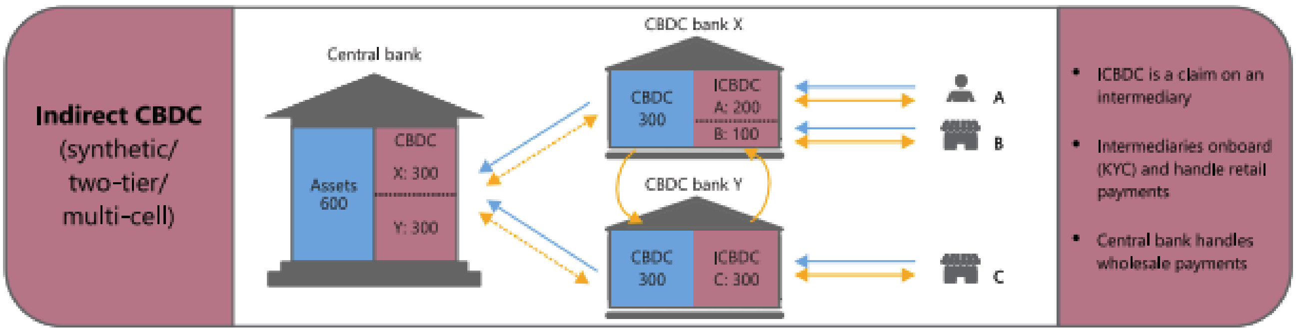

Figure 18 Indirect CBDC Source: (Auer and Böhme, 2020)

(Kumhof and Noone 2018) and (Adrian and Mancini-Griffoli, 2019) introduced the idea of a management scheme for a CBDC similar (but not identical) to the existing two-tier financial system. This concept later became known as “Two-tier CBDC”, “Synthetic CBDC”, or “Indirect CBDC”. For our purposes we will opt to use the term “indirect digital euro” as it complements the trifecta of direct, indirect, and hybrid digital euro. In a hybrid digital euro model, retail customers, meaning individuals, households and businesses, hold accounts with commercial banks and other depository institutions. Those retail accounts are backed 1:1 with digital euro held by commercial banks at the Central Bank. The digital euro would still be issued by and be a liability of the

European Central Bank. However, in contrast to the direct model presented above, it would be an asset of commercial banks, rather than retail customers.

In Section 1.1 we defined a retail digital euro as "a form of legal tender denominated in the national currency, to fulfil the necessary functions of money, serving as a medium of exchange, store of value, and unit of account, all while constituting a liability of the Central Bank and asset of the private sector, meaning individuals, households and businesses". An indirect CBDC "violates" this definition by not extending the claim to the wider private sector. As a result, the full benefits of direct claim with the central bank, such as the lack of credit risk, are not realised. Regardless, indirect architectures present an attractive option as they disrupt established processes and dynamics minimally compared to the other options. The commercial banking sector remains responsible for acquiring and onboarding customers, practicing the necessary due diligence, such as KYC/AML, manage the relationship with the end-user and resolve problems that might arise. Additionally, the structure and function on the current payments system and its various stakeholders will not be disrupted, at least not significantly.

However, the impact of a Federalist CBDC on credit creation may range from severe to marginal depending on the *theory of banking* that we subscribe to. Over the past couple of centuries, three theories have shaped the way economists perceive money creation, namely (1) the *financial intermediation theory of banking*, (2) *the fractional reserve theory of banking*, and (3) the currently prevalent *credit creation theory of banking*. All have enjoyed the support of top economists:

> (1) According to the financial intermediation theory, commercial banks are no different from other non-financial institutions, as in essence they receive deposits and simply re-allocate them in the form of loans.
>
> (2) Similarly, the fractional reserve theory suggests that individual commercial banks are but financial intermediaries that lend a part of the deposits they receive (say 90%), while keeping a fraction f (i.e., 10%) as 'reserves'. While in this manner each bank is not creating money, collectively the banking sector does create money through this system. To see how, each loan issued by a bank is viewed as a step in a linear sequence of similar steps by other banks. Since each new deposit D may come from a loan issued by another bank *that has not yet been repaid*, the resulting double-counting is tantamount to an increase in the overall monetary mass by the value of the new loan. Repeating this process indefinitely generates a geometric series of new money whose total value converges to xD, where $x = (1/f - 1)$ and is known as the money multiplier. For $f = 10\%$, $x = 9$.
>
> (3) Finally, the credit creation theory of banking suggests that commercial banks do not wait for new deposits and do not check their reserve position before issuing new loans. Therefore, they can *individually* create credit in the form of new deposits that appear in the accounts of the loan recipients. This means that they create money as "fairydust out of thin air" (Werner, 2014), without even the constraints of the fractional reserve system.

According to theories (1) and (2), an attractive CBDC (digital euro) would inhibit the ability of commercial banks to issue credit. In a scenario of an indirect digital euro that necessitates a 1:1 reserve ratio for digital euro accounts, commercial banks would need to comply with stricter reserve requirements. Consequently, with less available deposits, lending capacity would also be decreased, which could result in increases of the cost of money and interest rates in the wider economy. Conversely, according to theory (3), lending and cost of money would remain largely unaffected.[7]

Chapter 3: Digital Euro Design Options

Having explored the design space for a digital euro, we are ready to demonstrate how its various aspects interconnect to distinct options with unique features.

SECTION 3.1: ACCOUNT-BASED DESIGN OPTION

Option 1: Account-based RTGS Centralist Digital Euro

The first option available to regulators is that of an Account-Based RTGS Centralist Digital Euro, hereafter abbreviated as ARC Digital Euro. Such system would utilise account balances and make use of the Eurozone's existing RTGS as a remote ledger. The defining characteristic of such Centralist Digital Euro and the primary deviation from existing systems is that the ECB would be responsible for maintaining and managing end-user accounts. Naturally, TIPS would need to be modified to accommodate for this change. An overview of the accompanying benefits and perils of this transition is presented in Section 2.2.

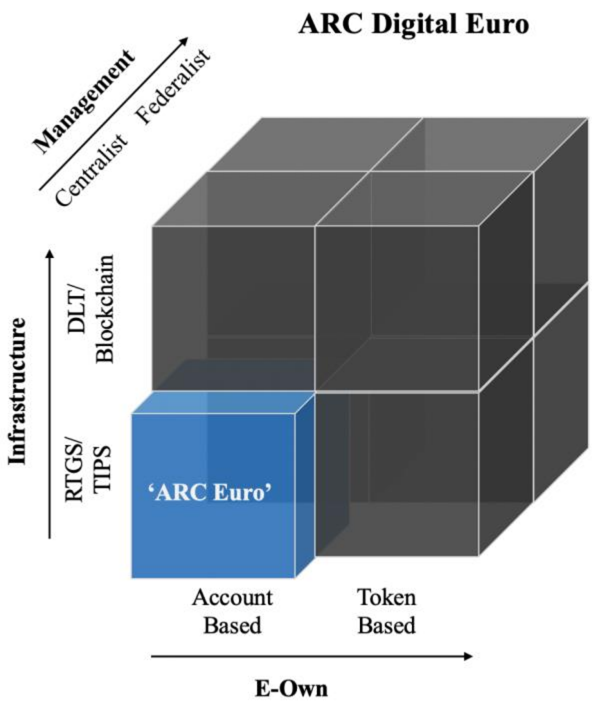

Figure 19 ARC Digital Euro Source: (EUBOF)

To demonstrate the shift in the nature of the payment's system as well as claims, we can examine how transactions would be actualised and settled under this new system. Currently transactions that involve end-user accounts held by the same commercial bank are handled by the consecutive debiting and crediting of the corresponding user accounts, as demonstrated in Figure 20. This is essentially the equivalent of a bank "taking money out of one pocket and putting it into the other". Interbank transactions, on the other hand, are settled through account reserves at the Central Bank, as shown in Figure 21. In an ARC Digital Euro system, all transactions would be handled by debiting and crediting accounts held with the Central Bank, instead of commercial banks. International transactions and cash withdrawals would be affected in an analogous manner.

Same bank txs

European Central Bank

Assets	Liabilities
Asset x	Liability x
Asset y	Liability y
Asset z	Liability z

Commercial Bank A

Assets	Liabilities
Asset x	Liability x
Asset y	-100 Account of A
Asset z	+100 Account of B

Commercial Bank B

Assets	Liabilities
Asset x	Liability x
Asset y	Liability y
Asset z	Liability z

Figure 20 Commercial bank interbank transaction model Source: (EUBOF)

Before

European Central Bank

Assets	Liabilities
Asset x	Liability x
Asset y	-100 Reserves of A
Asset z	+100 Reserves of B

Commercial Bank A

Assets	Liabilities
Asset x	Liability x
Asset y	Liability y
-100 Reserves	-100 Deposits A

Commercial Bank B

Assets	Liabilities
Asset x	Liability x
Asset y	Liability y
+100 Reserves	+100 Deposits B

After

European Central Bank

Assets	Liabilities
Asset x	Liability x
Asset y	-100 Account of A
Asset z	+100 Account of B

Commercial Bank A

Assets	Liabilities
Asset x	Liability x
Asset y	Liability y
Asset z	Liability z

Commercial Bank B

Assets	Liabilities
Asset x	Liability x
Asset y	Liability y
Asset z	Liability z

Figure 21 Central Bank transaction model Source: (EUBOF)

Depending on the specifics of this transition and its implementation, and the ECB's capacity to serve consumer needs at a high standard, this shift could either be disruptive or unnoticeable to end users.

Option 2: Account-based RTGS Federalist Digital Euro

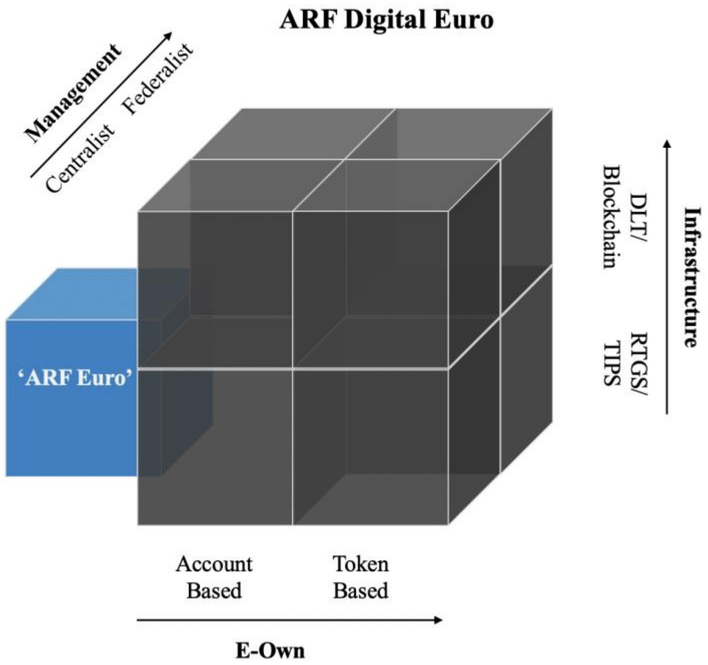

Figure 22 ARF Digital Euro Source: (EUBOF)

The next option for a European CBDC, is that an Account-based RTGS Federalist Digital Euro (ARF Digital Euro). Similar to the option presented above, an ARF Digital Euro system would utilise TIPS and account balances. However, as a Federalist system, commercial banks and other PSPs would still be involved in the payment system. If a Federalist Digital Euro is to operate in an indirect way, end user accounts would still be held with commercial banks and would be backed 1:1 with digital euros held with the Central Bank. Depending on the attractiveness and additional features of the European CBDC, payments and loan issuance could remain largely unaffected and would be handled by commercial banks. By many regards this can be thought as a reinvention of the existing system with more nuanced reserve requirements. In a hybrid Federalist system, commercial banks and other PSPs would adopt an adjunct position with their responsibilities diminished to managing the messaging layer and aspects of the end-user relationship. In either case, an ARF Digital Euro would bear the closest resemblance to existing systems and procedures, compared to any other option presented.

Option 3: Account-based DLT Centralist Digital Euro

The third option available to regulators is that of an Account-Based DLT Centralist Digital Euro, abbreviated as ADC Digital Euro. In such system, accounts are again utilised to keep track of user balances but, contrary to the two options presented above, the remote ledger for storing them would be a DLT instead of TIPS. An ADC Digital Euro could closely resemble a permissioned (private) blockchain deployment that utilises accounts, such as a private version of Ethereum, with the ECB serving as a single node for verifying transactions and other state transitions. Such account-based model would, among other things, keep track of the remaining balance in each account, and verify that each account balance is larger than or equal to each spending transaction amount.

Evidently the innovation of this model is the introduction of a DLT/blockchain as the remote ledger for recording balances. However, as noted in Section 2.2, the novelty of blockchains is lost in a system controlled by a single entity. Both TIPS and DLT rely on geographically distributed databases, with blockchains utilising a novel consensus mechanism that allows validators to determine the true state of the network. Naturally a system controlled by a single entity, in our case the ECB, does not necessitate a consensus mechanism. In that sense, the use of DLT may be redundant in a Centralist system, save perhaps for its marginal benefits of interoperability with deployments from the open blockchain sector.

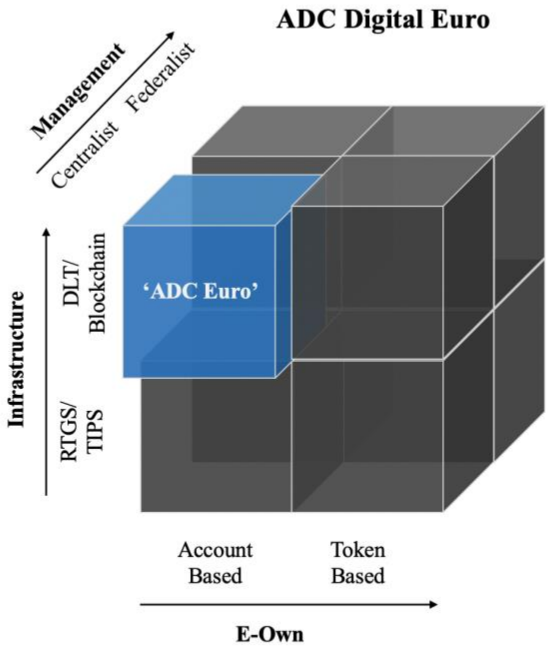

Figure 23 ADC Digital Euro option Source: (EUBOF)

Depending on its similarities with existing blockchain deployments, a DLT infrastructure for a digital euro could facilitate the interoperability between the regular economy and the open blockchain space. In simplistic terms, interoperability is the ability of different systems to interact and communicate with one another. In many cases this necessitates an intermediary solution that translates information on the state of one system to the other. The more similar the two systems, the less information must be translated and *vice versa*. A DLT infrastructure for digital euro, if similar to deployments found in the open blockchain space, would facilitate interoperability between the two by leveraging existing interoperable techniques (Cross-chain anchoring and pegging, atomic swaps, etc). Additionally, and again depending on the technical similarity of the systems, code originally written for decentralised applications could run natively on a digital euro, making innovative programmable applications available to non-crypto natives. Finally, an interoperable digital euro built on DLT could enjoy the benefits of bridge solutions developed in the open blockchain sector and be made available across the various deployments in the blockchain space. The above comes at the expense of an infrastructure aligned with current procedures and legislation.

Option 4: Account-based DLT Federalist Digital Euro

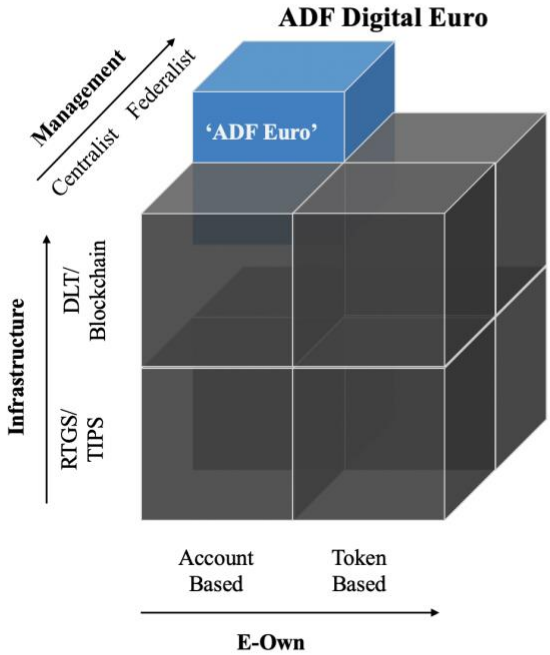

Figure 24 ADF Digital Euro option Source: (EUBOF)

The alternative is that of an Account-based DLT Federalist Digital Euro or ADF Digital Euro. An ADF digital Euro would utilise accounts as a record for user balances and DLT to store this information. However, in a Federalist system the DLT model makes intuitive sense, as the ECB, commercial banks, and other payment provides would facilitate for transactions, serving as the trusted nodes in a PoA blockchain. The nature of claims on a digital euro again relies on the type of federation. In an indirect system, a digital euro would be a liability of commercial banks, backed by reserve accounts, whereas in a hybrid model it would be a liability of the Central Bank. In terms of the fundamental features trade-offs of a DLT system, those would be identical to Option 3.

SECTION 3.2: TOKEN-BASED DESIGN OPTION

Option 5: Token-based RTGS Centralist Digital Euro

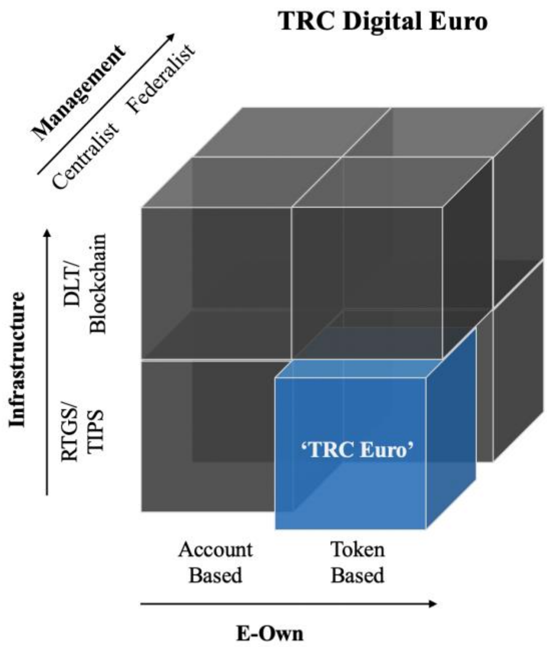

Figure 25 TRC Digital Euro option Source: (EUBOF)

The next option available to regulators is that of a Token-based RTGS Centralist Digital Euro, thereafter abbreviated as TRC Digital Euro. This system bears close resemblance to the first option presented here. However, instead of using accounts to record balances an Unspent Transaction Output (UTXO) system would be utilised instead. Each UTXO represents a certain amount of value. When a UTXO is spent, new UTXOs are created in its place that can be spent again later. This is analogous (but not identical) to how change received after purchasing a good or service with cash can be spent on some other good or service. As every UTXO is the result of another transaction, due to its digital nature, the digital euro itself would serve as an evidence of how the transaction was funded by previous transactions. As a Centralist system, in a TRC digital Euro the Central Bank would be responsible for and facilitate the transaction. To facilitate for this change, a modified version of TIPS would serve a dual purpose in this new UTXO system.

First, TIPS would serve the role of a memory pool, commonly referred to as 'mempool', for storing transaction information between transaction verification and transaction settlement. Secondly, it would also serve the role of what is often referred to as the 'chainstate'. The chainstate is a database for storing information on UTXOs in addition to other adjacent data (e.g. the block height). Naturally, since UTXOs enable a novel form of built-in accounting, with every UTXO being the result of another, the ledger capabilities of TIPS would become superfluous. In Centralist systems, TIPS, and consecutively the ECB, would be responsible for maintaining the only mempool and chainstate, whereas in Federalist systems, each participating institution would maintain their own.

Understanding UTXOs

Consider the example of Bob who hands over a €20 bill at Maria's coffee shop in exchange for a Latte. Assuming that the cost of the Latte is €5, Maria shall end up with the €20 bill and Bob will receive €15 in change, for an effective value transfer of €5. Similarly, in a token-based system, Bob's UTXO representing €20 of value would be destroyed first, and then new ones would be created. One for Maria with a total value of €5 representing the payment, and one for Bob worth €15 representing the change.

Option 6: Token-based RTGS Federalist Digital Euro

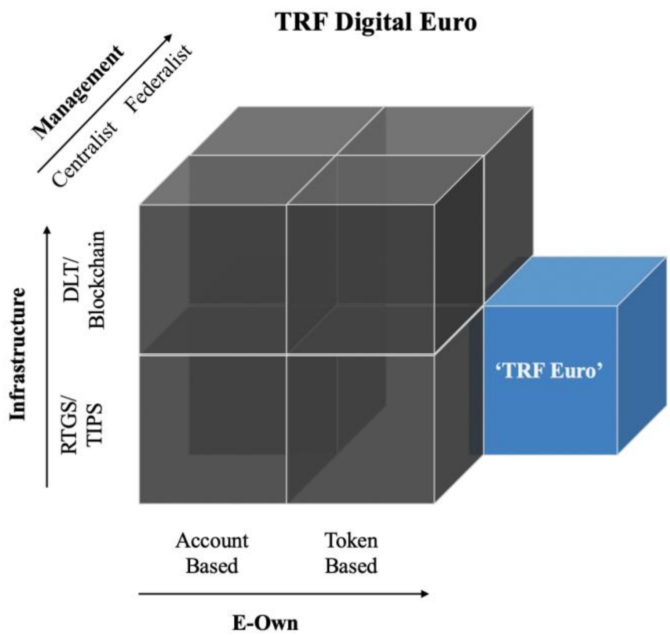

Figure 26 TRF Digital Euro Source: (EUBOF)

A Token-based RTGS Federalist Digital Euro (TRF Digital Euro) would bear close resemblance to the option presented above, as it would use a token/UTXO model in conjunction with TIPS. As a Federalist system, though, commercial banks and other PSPs would still be involved. Depending on whether the federation operates in a direct or indirect manner, their role and responsibilities would vary similarly to an ARF Digital Euro.

Option 7: Token-based DLT Centralist Digital Euro

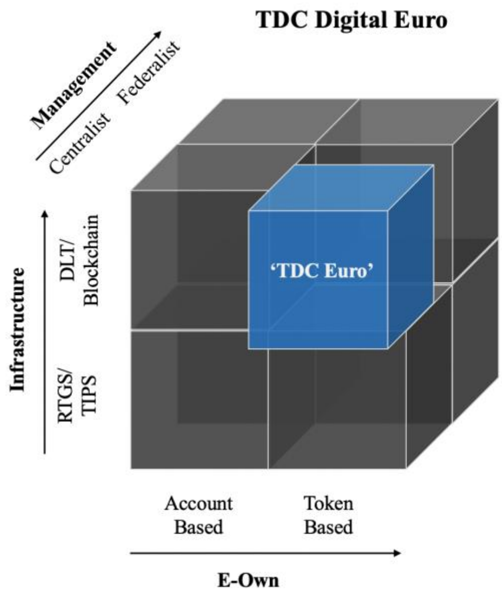

Figure 27 TRF Digital Euro Source: (EUBOF)

A token-based DLT Centralist Digital Euro or TDC Digital Euro would utilise tokens/UTXOs stored in a blockchain/DLT. Such system could closely resemble a permissioned Bitcoin deployment with the ECB acting as the sole validator. However, as demonstrated in the case of an ADC Digital Euro, DLT structures offer only marginal benefits over RGTS if controlled by a single entity.

Option 8: Token-based DLT Federalist Digital Euro

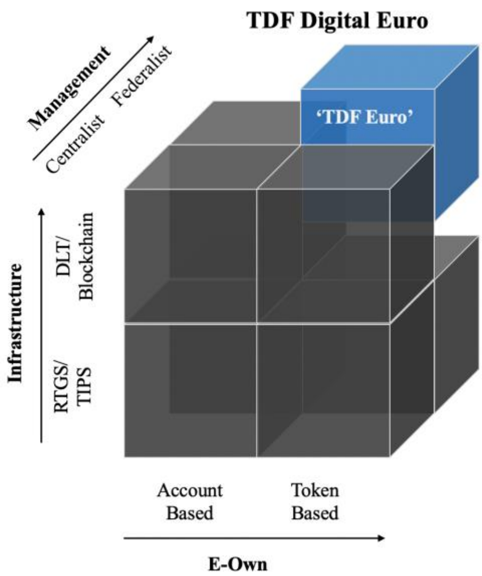

Figure 28 TDF Digital Euro Source: (EUBOF)

The last option available to regulators is that of a Token-based DLT Federalist Digital Euro, hereafter abbreviated as TDF Digital Euro. For its use of a token-based method as proof of ownership and authorisation of transactions, blockchain as a remote ledger, and a comparatively decentralised management scheme, this option could come closest to deployments from the open blockchain sector and would again closely resemble a permissioned Bitcoin system. In a TDF Digital Euro, the ECB, commercial banks, and other PSPs would work collaboratively in a PoA system to maintain a blockchain ledger of transactions. Depending on the nature of federation, the digital euro would either be a liability of the Central Bank or commercial banks.

SECTION 3.3: COMPARING DESIGN OPTIONS

Core requirements

With the derivative options for a digital euro defined, we are now ready to evaluate them against the requirements and prerequisites set by the ECB and presented in detail in Section 2.1. We assign a Yes/Possibly/No based on the degree to which each version of a digital euro satisfies each specification. The results are presented in a table, accompanied by justifications. Following the layout presented in Appendix 1 of the report on a digital euro, we start with the core requirements:

Prerequisite/ Requirement	Core requirements satisfied according to CDBC type:							
	ARC Euro	**ARF Euro**	**ADC Euro**	**ADF Euro**	**TRC Euro**	**TRF Euro**	**TDC Euro**	**TDF Euro**
Convertibility at par	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Liability of the Eurosystem	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
European solution	Possibly	Yes	Possibly	Yes	Possibly	Yes	Possibly	Yes
Market neutrality	No	Yes	No	Yes	No	Yes	No	Yes
Trust	Possibly	Yes	Possibly	Yes	Possibly	Yes	Possibly	Yes

Figure 29 Indication for core requirements satisfied by CDBC type Source: (EUBOF)

P1: Convertibility at par: In all potential alternative versions of a digital euro, convertibility with bank reserves, cash, or other forms of euro can be established as an absolute requirement and mandated by relevant legislation. From a technical perspective there will be two types of conversion regardless of its underlying ledger of management scheme: (1) the first pertains to shifting and the digital currency "deposits", to commercial bank deposits, and (2) the second, from digital euro to physical cash (as the ECB notes that they will remain available and an option). In Centralist and hybrid management schemes, shifting euro deposits to a digital euro, would consecutively alter the nature of the claim, from a liability commercial banks, to a liability of the Central Bank. Conversely, in an indirect model the end-consumer would be unable to maintain a digital euro directly. Instead, their account would be backed 1:1 with digital euro reserves, held by the commercial bank at the Central Bank. Finally, in all cases the digital euro would remain an asset of the private sector.

P2: Liability of the Eurosystem: The Eurosystem is comprised of the ECB and national banks of Europe's Member States. In every case presented, and regardless the infrastructure utilised, a digital euro is issued by the Central Bank and controlled either by the Central Bank alone, or jointly with commercial banks and other PSPs. Thus, it always remains a liability of the Eurosystem.

P3: European solution: As established in Sections 2.2 and 3.1, a Centralist Digital Euro would be –by definition- entirely controlled by the Central Bank, with the current role of commercial banks and PSPs drastically diminished. One could envision a scheme in which existing actors in from the banking sector are responsible for some parts of the distribution of the digital euro in adjunct positions, as service providers supervised by the ECB. In Federalist systems however, commercial banks and PSP would facilitate its distribution in more prominent positions.

P4: Market Neutrality: The market neutrality of a digital euro would rely both on its management scheme, as well as technical infrastructure options. Naturally, Centralist management would entirely disintermediate most if not all actors that are critical in the current implementation of the euro, such as commercial banks and PSPs. Consecutively, some of the services provided by private actors could become obsolete. Federalist schemes would also affect the operation and functions of the private sector, albeit not to such a drastic extent.

Options that relate to the technical infrastructure of the digital euro, such as its E-Own and remote ledger would also affect private solutions in the short term. Intuitively, the more a digital euro deviates from existing deployments in terms of its infrastructure, the more solutions offered by the private sector are likely to not apply. In every case, new private solutions could be developed tailored to the new characteristics and specifications for a digital euro. Whether that is allowed or facilitated is entirely dependent on policy decisions and the rules tied to the management scheme of the digital euro.

P5: Trusted by end users: Trust in a digital euro would largely depend on two factors, namely on its reliability from a technical standpoint, and the nature of the actors involved in its management and their relationship with consumers. For the most part, end users are unaware of the underlying infrastructure and technicalities of payment systems. For this reason, a sound implementation would most certainly enjoy the trust of end consumers regardless of its technical underpinnings, simply because the inner workings of the system would be, for the most part, invisible to them.

Concerning trust that relates to entities involved in the management scheme, we feel it is important to separate trust stemming from solvency and similar factors that relate purely to financial health, to trust founded on end-user relationships.

In terms of trust stemming from solvency, in a Centralist system entirely controlled by the ECB, users would enjoy the highest possible degree of protection and guarantees. In that sense concerns that relate to the financial health of the managing party and credit risk are eliminated. The protection and guarantees of the Central Bank are simply extended to Federalist systems that involve commercial banks, PSPs, and other actors. Depending on the implementation and the degree to which the same protections apply to indirect and hybrid schemes, users could enjoy a comparable degree of certainty as in systems entirely managed by the Central Bank.

Concerning trust developed through end-user relationships, Federalist schemes involving user-focused institutions are undoubtedly in an advantageous position when compared to a Centralist scheme managed by the Central Bank alone. That is because banks and similar institutions have developed consumer-focused expertise and infrastructure over centuries. Central banks on the other hand are responsible for functions that do not directly involve the end-user. In that regard, trust towards the Central Bank would rely on its capacity to develop and support end consumer relationships competently and swiftly after the launch of a digital euro.

Scenario specific requirements:

We now examine how options 1 through 8 satisfy scenario-specific requirements for a digital euro:

Prerequisite/ Requirement	Scenario-specific requirements satisfied according to CDBC type:							
	ARC Euro	ARF Euro	ADC Euro	ADF Euro	TRC Euro	TRF Euro	TDC Euro	TDF Euro
Enhanced digital efficiency	Possibly	Yes	Possibly	Yes	Possibly	Yes	Possibly	Yes
Cash-like features	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly
Competitive features	Possibly	Possibly	Yes	Yes	Possibly	Possibly	Yes	Yes
Monetary policy option	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Back-up system	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
International use	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cost saving	Possibly	Yes	No	Possibly	Possibly	Yes	No	Possibly
Environment friendly	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Figure 30 Scenario-specific requirements Source: (EUBOF)

R1: Enhanced digital efficiency: Digital efficiency would largely rely on the technological infrastructure for a digital euro. As underlined in Section 2.2., TIPS has proved an efficient, reliable and scalable infrastructure for the euro. An account or token-based digital euro deployed on TIPS would be almost identical to existing systems with regard to usability, convenience, speed, cost efficiency, and programmability, and would enjoy myriads of interoperable front-end solutions and interfacing with private payment schemes. While an alternative DLT infrastructure is comparatively an unproven solution, existing deployments and research do not suggest that private deployments of DLT would be inferior to an RTGS system in all important areas, including speed, efficiency, and reliability. Naturally, this largely depends on the specifics and soundness of its implementation. However, as a novel infrastructure, a blockchain solution for a digital euro would necessitate new systems and procedures to ensure its interfacing with existing front-end solutions from the private sector.

In every case, Centralist systems operated solely by the Central Bank would necessitate the vast expansion of its infrastructure, operations, and mandate. Depending on the speed and quality of those shifts, usability, convenience, speed, cost efficiency may or may not suffer in the interim. Federalist solutions, on the other hand, would rely on the admittedly agile private sector to implement any changes.

R2: Cash-like features:

For CBDCs, cash-likeness pertains to the level of accessibly, privacy and immediacy of transaction settlement. In terms of privacy, this debate falsely revolves around the use of accounts or tokens as an E-Own, with tokens promoted as the most cash-like solution, as we demonstrated in Section 2.2. In reality, neither system is, nor could ever be a perfect equivalent of cash. In contrast to transactions with banknotes and coins, digital payments necessarily generate digital fingerprints. Regardless of the data minimisation techniques that could be employed, given enough time and resources those digital traces could be linked to the transacting parties. Moreover, as we demonstrated in Sections 2.2 and 3.1, a digital euro would necessitate a digital ledger. Regardless of its nature, a ledger would necessarily store this digital fingerprint and make it available to third parties for verification. Additionally, the sole involvement of a third party to facilitate for the transaction makes CBDCs disanalogous to cash. Even in a theoretical and unlikely scenario where a perfect solution for anonymous digital payments is available, existing regulation would require some digital payments to be eponymous (Sveriges Riksbank (2018) (E-krona project report 2). Simply put, complete anonymity with CBDCs is likely unattainable. Concerning the immediacy of transaction settlement, both TIPS and DLT systems could allow for immediate transfer of funds and finality.

One additional consideration of cash-likeness is the availability of a digital euro to vulnerable and financially excluded groups. The rise of Fintech and Neobanks and Decentralised Finance has demonstrated how smartphones and other technological advancements could be used to bank the unbanked.

However, whether those innovations are adopted would largely depend on the motives of the entities involved in the management scheme of a digital euro. On the one hand, in a Centralist system where the euro is controlled by the ECB, the mandate of the Central Bank could shift to encompass financial inclusion. The success of its mission would largely depend on its capacity to develop and support the necessary infrastructure. Federalist systems on the other hand would rely on the motives of commercial banks and PSPs. Currently, commercial banks, as for-profit institutions, seek to maximise their returns by not engaging in unprofitable operations. It is not hard to imagine a scenario where their services are not made available to individuals simply as a result of a cost-benefit analysis, as is currently the case. Additionally, and depending on the reliance of the digital euro on strong identity ties, many vulnerable groups may lack the funds, education, or infrastructure to produce satisfactory identity proofs. As a result, they would be de-facto excluded from such a system.

R3: Competitive Features: As demonstrated, a digital Euro based on TIPS would offer features that are comparable to existing deployments. Additional features, complex programmable transactions, and interoperability with non-sovereign deployments could be achieved through intermediate solutions. However, novel applications of programmable money developed in the open blockchain sector and examined by foreign central banks are in many cases native to DLT systems. In that sense, and as demonstrated in part 3.1, under option 3, a DLT-based digital euro that draws from existing permissionless deployments could natively support programs and applications originally developed for open blockchains. While it is unlikely that features such as flash loans, or automated market makers would be implemented in a digital euro, the functionality that underpins them would still be available to regulators and will likely inform derivative novel features.

R4: Monetary policy option: A digital euro regardless of its infrastructure could be remunerated at interest rates influenced by the Central Bank. In every option presented above, shifts in interest rates would influence end-consumers directly, effectively disintermediating the existing mechanism for the transmission of monetary policy. Additional novel monetary policy tools are presented in Section 5.2 of this report.

R5: backup system: As demonstrated in Section 2.2 both TIPS and blockchain systems, despite their relatively recent introduction, have proven resilient and reliable systems.

R6: International use: As demonstrated in Section 2.2, both TIPS and blockchain systems offer options for and could facilitate for international use.

R7a: Cost saving: One important distinction concerning the costs associated with the introduction of a digital euro, is that of the initial versus fixed and variable operational costs. Initial costs are those that are incurred as part of the design and deployment of the infrastructure and related policy changes necessitated by a European CBDC. Fixed and variable costs on the other hand relate to the costs of operation. Intuitively, the more novel the infrastructure of a digital euro, the more **initial costs** it would necessitate through extensive planning, pilots and actual infrastructure deployment. Additionally, in Centralist schemes, the costs of developing and managing the infrastructure are to be incurred by the Central Bank, while in Federalist they are shared between the ECB and the various participating entities. Naturally, the operational costs associated with a digital euro deployed on TIPS would be comparable to existing systems. In the open blockchain space, most of the "operational" costs associated with DLT deployments stem from inefficient consensus mechanisms. While those serve a purpose in trustless systems, a digital euro under a PoA system would not incur similar costs.

R7b: Environmentally friendly: As noted, networks of mutually distrusting nodes rely on novel labour or reward/punishment schemes to ensure that participants remain honest and achieve distributed consensus. However, as demonstrated in Section 2.2, a digital euro that operates in a PoA would not necessitate consensus mechanisms explicitly tied to the consumption of natural resource (e.g. electricity). In every case, a digital euro would have an environmental fingerprint that is comparable to existing deployments.

General Requirements

Finally, we examine how each option satisfies the general requirements for a digital euro.

Prerequisite/ Requirement	General requirements satisfied according to CDBC type:							
	ARC Euro	ARF Euro	ADC Euro	ADF Euro	TRC Euro	TRF Euro	TDC Euro	TDF Euro
Control money in circulation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cooperation with market participants	No	Yes	No	Yes	No	Yes	No	Yes
Compliance with regulation	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly
Safety and Efficiency for European goals	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Accessibility throughout the euro area	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly
Use by non-EU area residents	yes	yes	yes	yes	Yes	Yes	Yes	Yes
Cyber Resilience	yes	yes	yes	yes	Yes	Yes	Yes	Yes

Figure 31 General requirements Source: (EUBOF)

R8: Ability to control the amount of digital euro in circulation: To avoid the use of a digital euro as an ultimate investment vehicle and safe haven and minimise the possibility of bank runs and disruptive events, the ECB could limit its attractiveness by design and through fixed or adjustable policies. Relevant techniques are presented in Section 5.1 and can be applied to a European CBDC regardless of its infrastructure and management scheme.

R9: Cooperation with market participants: Drawing from our analysis on P4: Market neutrality, Federalist schemes would facilitate cooperation with stakeholders from the private sector, and alignment with market best practices.

R10: Compliance with the regulatory framework: In every case, the introduction of a digital euro would necessitate changes in the existing regulatory framework. Shifts in the mandate and role of the Central Bank, the responsibilities and duties of commercial banks, the legal status of digital money, are just a few of the areas where adjustments would need to be made.

R11: Safety and efficiency in the fulfilment of the Eurosystem's goals: The safety and efficiency of a digital euro would rely both on its underlying infrastructure and management scheme. As demonstrated in the previous chapters, both TIPS and DLT can be used as an infrastructure for an efficient and safe payments system. In terms of the management infrastructure, the efficiency would rely on the entities involved. As we have noted, Centralist schemes managed entirely by the Central Bank would necessitate the development of a vast supporting infrastructure. Federalist systems on the other hand, can and likely will rely on private entities, as such costs will be distributed. However, both schemes can be designed to be safe and efficient.

R12: Easy accessibility throughout the euro area: The accessibility of a European CBDC throughout the euro area would depend on the interfacing of its infrastructure with existing front-end solutions, its cash-likeness and the degree to which it is made available to those currently financially excluded. As we have demonstrated in P3 and R2, this could be achieved regardless of its technological characteristics.

R13: Conditional use by non-euro area residents: All CBDC options presented here could be made available to individuals and businesses beyond the euro-area. The specifics of how this can be achieved are presented in Sections 4.1 and 5.2.

R14: Cyber Resilience: As demonstrated in Section 2.2, all options presented offer a comparable and high level of security and resilience to cyber threats.

Final assessment

To assess the attractiveness of each option in relation to the others we assign one (1) mark each time an option satisfies a prerequisite or requirement, noted with 'Yes' in the figures above, half a mark (0.5) each time an option could satisfy a prerequisite or requirement, noted with 'Possibly' in the above figures, and finally, zero marks (0), each time an option is not likely to satisfy a prerequisite or requirement. In our evaluation we assumed that all prerequisites and requirements are equally desirable. As such, we opted not to weigh options differently. The final marks are presented in descending order:

	Total 'Yes'	Total 'Possibly'	Total 'No'	Total Marks
ARF Euro	16	4	0	**18**
TRF Euro	16	4	0	**18**
ADF Euro	16	4	0	**18**
TDF Euro	16	4	0	**18**
ARC Euro	10	8	2	**14**
ADC Euro	11	6	3	**14**
TRC Euro	10	8	2	**14**
TDC Euro	11	6	3	**14**

Figure 30 Final assessment Source: (EUBOF)

According to Figure 31 (next page), the design options for a digital euro can be separated into 2 distinct categories. With options ARF, TRF, ADF, and TDF ranking as equally attractive for a digital euro, and, ARC, ADC, TRC, TDC options as equally less attractive. Upon first inspection, the above results further cement the 3 assumptions explicitly stated throughout this report.

1. **Federalist schemes are more attractive when compared to Centralist schemes**, as the former promote accessibility throughout the euro area, market neutrality, trust, enhanced digital efficiency, lower (shared) costs, and cooperation with market participants. This is apparent when we compare all options and exclude all prerequisites/requirements satisfied by every option, and further cemented if we opt to disqualify the options that do not comply with the prerequisites for a digital euro.

	Federalist Options satisfied according to CBDC type				Centralist Options satisfied according to CBDC type			
Prerequisite/ Requirement	**ARF Euro**	**TRF Euro**	**ADF Euro**	**TDF Euro**	**ARC Euro**	**ADC Euro**	**TRC Euro**	**TDC Euro**
European solution	Yes	Yes	Yes	Yes	Possibly	Possibly	Possibly	Possibly
Market neutrality	Yes	Yes	Yes	Yes	No	No	No	No
Trust	Yes	Yes	Yes	Yes	Possibly	Possibly	Possibly	Possibly
Enhanced digital efficiency	Yes	Yes	Yes	Yes	Possibly	Possibly	Possibly	Possibly
Cash-like features	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly
Competitive features	Possibly	Possibly	Yes	Yes	Possibly	Yes	Possibly	Yes
Cost saving	Yes	Yes	Possibly	Possibly	Possibly	No	Possibly	No
Cooperation with market participants	Yes	Yes	Yes	Yes	No	No	No	No
Compliance with regulation	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly
Accessibility throughout the euro area	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly

Figure 31 Centralist and Federalist schemes comparison Source: (EUBOF)

2. In every case, **the design choice between token and account-based systems is not a material one**. See Figure 34 (next page).

	Account-based options satisfied according to CBDC type				Token-based options satisfied according to CBDC type			
Prerequisite /Requirement	ARF Euro	ADF Euro	ARC Euro	ADC Euro	TRF Euro	TDF Euro	TRC Euro	TDC Euro
Convertibility at par	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Liability of the Eurosystem	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
European solution	Yes	Yes	Possibly	Possibly	Yes	Yes	Possibly	Possibly
Market neutrality	Yes	Yes	No	No	Yes	Yes	No	No
Trust	Yes	Yes	Possibly	Possibly	Yes	Yes	Possibly	Possibly
Enhanced digital efficiency	Yes	Yes	Possibly	Possibly	Yes	Yes	Possibly	Possibly
Cash-like features	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly
Competitive features	Possibly	Yes	Possibly	Yes	Possibly	Yes	Possibly	Yes
Monetary policy option	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Back-up system	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
International use	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cost saving	Yes	Possibly	Possibly	No	Yes	Possibly	Possibly	No
Environmentally friendly	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control money in circulation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cooperation with market participants	Yes	Yes	No	No	Yes	Yes	No	No
Compliance with regulation	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly
Safety & Efficiency for European goals	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Accessibility throughout the euro area	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly	Possibly
Use by non-EU area residents	yes	yes	Yes	yes	Yes	Yes	Yes	Yes
Cyber Resilience	yes	yes	Yes	yes	Yes	Yes	Yes	Yes

Figure 34 Design criteria comparison Source: (EUBOF)

3. **Blockchain/DLT is in most cases redundant when trusted parties are involved**. As such, the only material consideration between a digital euro deployed on TIPS, versus a digital euro on the blockchain is that blockchain/DLT enables native programmability at the expense of additional costs for developing this new infrastructure.

This trade-off is evident when we compare Federalist options and exclude all Prerequisites/Requirements equally satisfied by all options:

Prerequisite/ Requirement	**Exclusive requirements satisfied according to CDBC type:**			
	ADF Euro	**TDF Euro**	**ARF Euro**	**TRF Euro**
Competitive features	Yes	Yes	Possibly	Possibly
Cost saving	Possibly	Possibly	Yes	Yes

Figure 35 Federalist options with exclusive prerequisites/requirements Source: (EUBOF)

While competitive features introduced with the rise of Fintech and Neobanks, such as AI-financial advisors, big data analytics, mobile payments, Regtech, and Insurtech, to name a few, could be replicated by a digital euro based on TIPS, Europe's RTGS does not explicitly facilitate for the level of security and computational complexity enabled by 'smart contracts'. Smart contracts are self-contracts with their terms defined in code that lives on a blockchain/DTL network. The code controls the implementation of the contract and accompanying transactions and state transitions without the need for third parties. While seemingly a mundane concept, smart contracts have enabled a vivid ecosystem of Decentralised Applications (dApps) and Decentralised Finance Applications (DeFi) in the open blockchain space, that initially replicated and arguably iterated on functions of the traditional financial system. Smart contract-enabled applications are seen as a way to reduce costs, by not requiring intermediaries, and increase security by automatically enforcing rules and eliminating human error (Nick Szabo, 1997) (Fries and Paal, 2019). Additionally, due to their deterministic nature smart contracts allow for novel financial applications, such as Flash Loans that cannot be replicated in traditional systems.

A digital euro deployed on a blockchain infrastructure that supports an expressive programmable environment (e.g. an Ethereum Virtual Machine compatible blockchain), would enable competitive features that are comparable to those offered in the open blockchain space, but also backed by the protection and guarantees of the Central Bank. Moreover, open-source code originally composed for dApp or DeFi applications would be natively supported on a digital euro, bootstrapping the development of applications. Finally, an EVM compatible digital euro, would also benefit from interoperable solutions and standards developed for the open blockchain space.

However, a CBDC deployed on a traditional infrastructure, such as Europe's RTGS would not be able to natively replicate the functionality of smart contracts. To mitigate this, there is the option of 'Programmability by Proxy'. In such a scenario, a digital euro would rely on a non-native system (permissioned or permissionless DLT, database, or otherwise) for its programmable functions with the results 'fed' into TARGET/TIPS and ultimately settled in (digital) euro. Such applications of programmability by proxy have already been developed. Most recently, Deutsche Börse, Deutsche Bundesbank and Germany's Finance Agency successfully tested a framework that allowed for electronic security deployed on permissioned DLT, to be settled in central bank money (Deutsche Börse, 2021).

To the extent that basic instructions can be translated between the two systems, there is nothing to suggest that schemes can't be devised to facilitate more complex exchanges. In that sense a CBDC deployed on TARGET/TIPS could achieve complex programmability by proxy. Naturally, the question becomes one of resilience of intervening solutions, and of cost-benefit versus systems with native programmability.

Chapter 4: Technical and User-Focused Considerations

SECTION 4.1: INTEROPERABILITY

Broadly speaking, interoperability refers to the technical ability of two or more disparate systems to exchange information in a manner that maintains the "state and uniqueness" of the information being exchanged[1] (World Economic Forum, 2020b). However, the concept of interoperability, especially as it relates to CBDCs (such as a digital euro), is complex and dependent not only on the nature of the various systems and information that are being connected but also on the level of trust that stakeholders are willing to put into those systems.

Additionally, the purpose for exchanging information has important consequences on the potential options and frameworks available. For example, exchanging one digital asset for another is very different than using information on one system to affect the state of another system.

Whether a CBDC is built on a traditional real-time gross settlement (RTGS) system or based on a distributed ledger technology (DLT) system, it is assumed there could be a strong preference for the CBDC to be interoperable with other systems, whether those are existing payment systems, permissioned, or permissionless blockchain-based solutions. As such, before providing a more detailed description of the interoperability frameworks available, it's essential to understand the current restrictions that limit communication with blockchain-based systems, and the importance of trust related to these communications.

Limitations of Blockchain-Based Systems

"Distributed systems have to make trade-offs to function effectively in an asynchronous environment like the Internet - one without a global clock to define the ordering of events," according to Aleks Larsen of Blockchain Capital (Larsen, 2018). The result is that there is no single blockchain suited for all use cases -- there is no "one-size-fits-all" solution. Instead, a myriad of purpose-built chains are designed and optimized for specific features, such as increased security, transaction throughput, enhanced privacy, or platform complexity.

For example, the Bitcoin blockchain is often seen as having greater security than the Ethereum blockchain. Meanwhile, Ethereum's comparatively more expressive programming languages (Solidity/Vyper) allows for the development of decentralized financial applications (often referred to as "DeFi"), which are not possible on Bitcoin. However, as Larsen notes, "Bitcoin can't speak the language of Ethereum and vice versa." As a result, if someone wants to use Bitcoin in a DeFi application on Ethereum, they will require an interoperability mechanism that effectively bridges the gap between these two blockchains.

In order to create a "bridge" to a specific blockchain, a communication channel needs to be set up with that chain. However, blockchains are passive entities -- they can receive messages, but they have no way of sending messages. Thus, a bridge requires two independent, one-way communication channels. This method is often referred to as "dual simplex" communication.

Furthermore, blockchains can only update their internal state by processing a transaction. This means these one-way communication channels require active off-chain actors to maintain communication. Therefore, a bridge from an origin source (this could be either a legacy RTGS system or a DLT-based blockchain) to a specific blockchain destination requires an off-chain actor to actively monitor the origin source for any messages or state changes that need to be conveyed to the destination blockchain. If a message is detected, the off-chain actor will effectively translate this message or state change into a transaction that is dispatched to the destination blockchain for processing.

Importance of Trust Models

Given the prominent role of the off-chain actor in maintaining the communication channel, it is critically important for the destination chain to authenticate the messages it receives properly. Therefore, the trust model associated with off-chain actors is vitally important. Broadly, there are two options: a trusted model or a trustless one.

The trusted model is based on the premise that the destination (or receiving) chain selects an off-chain actor or group of actors (sometimes called a "federation") that it trusts to process messages. Any messages received by this actor, or federation, are deemed to be authentic and valid by the destination chain. This model, often referred to as a "notary scheme" or "proof of authority," is viewed by many, including Larsen, to be the simplest form of cross-chain interoperability. In the context of a digital euro, this federation could involve entities such as the Central Bank, commercial banks, financial services providers, or other appointed public and private actors.

Although such a model is fast and cheap to validate, the main disadvantage of the trusted model is that power is concentrated and centralized in a single actor or a small federation of actors. Should this actor (or group of actors) become compromised, the result could be catastrophic for the system.

Instead of trusting a small group of actors, a trustless model can be used to create a bridge between two blockchain systems by utilizing what's known as a "relay," effectively allowing the receiving chain to verify the state of the sending chain independently. The process is more complex than the trusted model, but Larsen offers a helpful description of the process:

"A relay is a contract on chain A that functions as a light client of chain B, using chain B's standard verification procedure to verify block headers fed into the contract. This gives chain A the ability to understand event changes on chain B…"

By allowing one blockchain to understand event changes on another directly, we can take advantage of the trustless option, decentralizing power away from a small concentration of actors. Effectively anyone can relay the sending chain's message to the receiving chain because the message will contain all of the data necessary for the receiving chain to validate the message, instead of relying on the messenger. However, the disadvantage to such a system is that the data required to validate the state of the sending chain may be extremely large, rendering the process slow and prohibitively expensive[2].

A "Purpose-Based" Approach to Interoperability

As noted earlier, the potential options and frameworks available are largely dependent on the purpose or need for interoperability. Both Larsen and the World Economic Forum report offer two categories that provide a useful "purpose-based" context for interoperability -- specifically the exchange of digital assets and the exchange of arbitrary data[3].

Digital Asset Exchange

The idea of a digital asset exchange, as it relates to CBDC, effectively describes the ability for a digital euro to be exchanged for that of another country's CBDC (such as a digital dollar), assuming both CBDCs are issued on separate and distinct systems. Alternatively, this may also be used to describe the scenario whereby a digital euro, issued on one network, is used to purchase a euro-denominated digital asset, such as a security or bond, issued on another network.

If a digital euro, built on a legacy RTGS system, needs to interact with digital assets or services issued on a separate DLT-based blockchain network (such as a security or another country's CBDC), it's likely that some type of "oracle" would need to be utilized. As the World Economic Forum's whitepaper on *Bridging the Governance Gap: Interoperability for Blockchain and Legacy Systems* notes: "blockchains do not natively...provide connections to traditional systems," as such, "oracles serve as an external source of data for DLT systems" (World Economic Forum, 2020a). However, the European Central Bank (ECB) may wish to utilize a permissioned oracle network of vetted and trusted participants instead of the decentralized, permissionless option discussed in the WEF whitepaper.

If distributed ledger technology is used for the issuance of both a digital euro and the corresponding asset for which it is to be exchanged, then more options are available to affect this exchange. Similar to the oracle model above, a notary scheme, as mentioned earlier, could be utilized, whereby an off-chain actor (or federation of actors) could be entrusted to validate the transactions. Alternatively, relays could be employed to validate transactions in a trustless manner, as described earlier. Finally, such a scenario could utilize a hashed timelock contract (HTLC, also known as an "atomic swap").

Atomic swaps require both parties of a transaction to escrow the digital asset they wish to exchange in Hashed TimeLock Contracts (HTLCs), effectively allowing the parties to exchange their digital assets without a trusted third party. Although atomic swaps are well known, with Larsen calling them "the most practical technical approach to interoperability," they are not without their limitations. In fact, there are a number of mechanisms through which atomic swaps can be manipulated or attacked, including the free option problem, liquidity trolling, and the sleeping vulnerability[4].

At this point, it is important to note the difference between interoperability and usability. While an application such as a digital wallet that allows users to interact with assets on multiple chains may provide a more user-friendly experience, it does not make those chains interoperable[5]. This is because the chains are not actually communicating with one another -- instead the app acts as a trusted intermediary, relaying information from multiple chains to the user.

Arbitrary Data Exchange

The more difficult type of interoperability, but also the one that offers more exciting and ambitious projects aimed at "unlocking full cross-chain communication," is the exchange of arbitrary data, according to Larsen. For example, by allowing data on one chain to affect the state of another chain, the power of DeFi applications like micro-lending or micro-insurance can be realized.

Returning to the case of the digital euro, it is perhaps fair to assume that, should a digital euro be built on a DLT-based system, such a system would likely be permissioned and centralized. Additionally, the ECB is likely to grant access to traditional financial institutions, such as banks and exchanges, which are highly regulated. Meanwhile, smaller fintech start-ups building innovative DeFi applications are not likely to have access to these permissioned networks and thus will build such apps on public, decentralized blockchains like Ethereum, Celo, and Polkadot.

In order for a digital euro to be used in these DeFi applications, the public blockchain hosting the application will need a way to verify the validity of the private blockchain where the digital euro is issued. As highlighted earlier, the options available for interoperability ultimately come down to a decision based on what level of trust is deemed acceptable.

According to Larsen, who cites a paper by the founder of Ethereum (Vitalik Buterin), there are two primary technical approaches for achieving interoperability with respect to the exchange of arbitrary data: notary schemes, requiring a trusted off-chain actor (or federation of actors) to validate transactions, or the use of relays, which validate transactions in a trustless manner.

No matter what option is chosen or what degree of trust is relied upon, the need for interoperability to help unlock the power of digital assets (including CBDCs) is clear. Standardization and widespread adoption of interoperability architectures could help companies and end-users overcome the limitations of any given chain, while simultaneously taking advantage of the unique strengths of supported chains. If accomplished, blockchains could become far more efficient, user-friendly, and viable across sectors.

SECTION 4.2 – PROGRAMMABILITY

Programmability is the ability to modify the behaviour of a system or the behaviour of a subsystem by providing a new set of instructions or tasks. The nature of the instructions that can be used to modify behaviour at runtime is completely dependent upon the type of programmability which the system supports. For example, consider a system that allows users to transfer money to each other. The base implementation which allows a user to transfer money would likely not be desirable to be able to be changed or programmable by the user or any other stakeholder. However, allowing for a user to specify that any time they receive funds in their account, that say 15% is automatically sent to another account, may be a desirable feature (perhaps the account holder wants to save 15% of their income). This is an example of programmability – which allows for some level of configurability in regard to actions that can take place potentially before or after a transaction. Indeed, programmability could even allow for aspects of the transaction itself to be able to be changed – however that is a design option that needs to be decided for the specific case at hand.

The two main benefits to providing programmability in the context of a digital payments are: (1) various processes associated with payments can be automated enabling for more efficient processes (not only internally within the banking structures, but to all other stakeholders using CBDCs); (2) they can be automated in a manner that is trusted, undisputable, verifiable and that allows for various stakeholders to fully trust and enter into (digital and automated) agreements with other parties. This trust is built through guarantees provided through the CBDC system. This is exactly what smart contracts on top of DLTs provides, a means to agree to digital processes amongst different parties, without the ability for any party to modify the code that will be automatically executed. We'll discuss issues pertaining to implications of executing smart contracts on DLTs or other systems later in this section.

In this section, we'll first discuss the spectrum of options in which programmability can be provided (in general), thereafter discuss ideal programmability options within the context of a CBDC, we'll then present some use-cases to exemplify programmability models that would be required for such use-cases, and then discuss how choosing a DLT or a traditional RTGS system may impact programmability.

Programmability of systems in general

The flexibility to which programmability can allow for is completely dependent upon how the system is designed. The extent to which programmability can be supported can range from:

(1) limited predefined actions that can take place for which users can provide parameters for. An example of a predefined action would be to automate initiate execution of a transaction upon receiving funds (similar to the example provided above) or sending an email or some other signal that could be used to alert an external system to initiate a task. However, such a predefined task (or template) paradigm implies that the extent of programmability and flexibility is limited to the actions that have been provided to the user by the system providers (i.e., what the CBDC implementation inherently supports); to, at the other extreme, (2) completely flexible programmability allowing for users themselves to define what code and actions will be undertaken. Such an unrestricted level of programmability is typically achieved through a general-purpose programming language. and, (3) any level of programmability in between (1) and (2) above.

Programmability Design Options in the context of CBDCs

The extent to which programmability could be provided could go all the way down to a general-purpose language framework like Java, .NET, Python and C/C++ (and others) – however, a CBDC need not allow users to program whatever they like, but should allow CBDC users programmability to be able to achieve useful actions whilst limiting scope to programmable features that should be directly related to CBDCs and associated transactions. Therefore, let's generalise the range of flexibility/programmability to **three design options** in aim of getting a better idea of the type of programmability that is desirable to have in a CBDC:

(1) **parameter-only** programmability;

(2) **domain specific language (DSL) or visualisation** programmability; or

(3) a **smart contract-like language** that is general purpose enough which can provide flexibility to encode logic according to need, yet at the same time limited enough so that the scope of the language allows for the automation of only processes that are directly related to CBDCs and associated transactions.

Scoring: 0 = Low, 10 = High	Parameter-only (template)	Domain Specific Language (DSL) or Visualisation	Smart Contract-like Language
Ease of use	10	5	0
Level of configurability provided to users	0	5	10
Level of support users will require; and likelihood of users making mistakes	0	5	10

Figure 36 Design options comparison Source: (EUBOF)

CBDC Programmability - Indicative Use-cases & Programmability Models Required to Support them

To highlight the levels of programmability required, consider the following use-cases that could be automated using CBDCs:

Automated VAT Settlement

A merchant could agree to **opt-in** to an automated VAT settlement system. Whilst, the system could be implemented in various ways, the key here is that merchants could automate their VAT payments and governments could also automate any refunds due. The implications of such a system would be largely beneficial (less time 'wasted' on VAT reconciliation from both a government and merchant perspective; less mistakes; less VAT fraud). Indeed, an incentive may be required to entice merchants to opt-in to such a system, though the reduced accounting overheads and costs may be enough to entice many.

Levels of Programmability Required:

Smart contract-like language or a DSL for Government to define VAT settlement system rules – since different governments have different rules;

A **parameter/template interface** that allows merchants to opt-in/out (and potentially additional options) The parameter/template interface would ideally be automatically generated either from the smart contract-like language or DSL.

Trade Finance and other Retail-based Delivery Automated Payment Release use-cases

Much of the bureaucracy involved in trade finance could be reduced to nothing more than the clicking of a few buttons. The recipient could be assured through their CBDC interface that the purchaser's funds are blocked and will be released upon confirmation of receipt. The purchaser is assured that their funds are blocked and have not left their account until purchased goods have been received. In such a use case a third party would be required to verify receipt (just like existing trade finance processes do today), however all the other bureaucracy could be removed – because all parties involved would have guarantees provided through the CBDC system.

The same could apply to other types of online purchases. Such a process could make use of two options: (1) either couriers could play a part in the process (to confirm delivery); or (2) a payment could be blocked and only released when either the buyer releases payment or after a set period if no claim that the package was not received is not raised. This would greatly reduce the need for chargebacks. Such use-cases could also include multiple-party automated agreements, e.g. the courier may agree with the sender that payment for delivery is only released upon delivery; a sender may also require some form of compensation/guarantee that would be paid to the sender if the package/shipment is lost; the buyer agrees to pay the sender only if the delivery is received and the sender knows that the buyer's funds are blocked for release upon delivery. All parties can have such conditions guaranteed through smart contracts – with real-world evidence of delivery/non-delivery confirmed by a trusted party (which could be the bank, the courier, or any party deemed trustworthy in the particular use-case).

Levels of Programmability Required:

Trade finance agreements and processes often have specific requirements that can be complex. Therefore, a **smart contract-like language or a DSL** is required so that either CBDCs, banks, or even potentially merchants can design their own processes.

A **parameter/template interface** that allows either merchants themselves, or banks (OBO merchants) to enter into such agreements.

Notary Services

Notaries often hold on to client funds for various agreements, e.g. when purchasing property. This process, though cumbersome, allows for parties to build mutual trust through the notary that their interests are safeguarded. This process can be automated through the use of programmable features of CBDCs. As in case 2 above, an entity is needed to verify that an action in the real world has taken place. Banks could, in such a scenario, play a crucial role as the trusted parties that would provide the required trusted input allowing for smart contracts to release payment or otherwise.

Programmability Required:

A **parameter/template interface** that allows for involved parties themselves, or banks (OBO parties) to enter into such agreements.

Such standard parameter/template interfaces can be designed by CBDCs/banks and/or potentially other players through the use of a **smart contract-like language or a DSL**.

Automated Payment Schemes and Automated Process Initiation upon Payment

Whilst substantial payments for online shopping/services pass through credit/debit card processing services, bank transfer payments for online shopping/services create barriers for their integration – since it often involves a manual process to verify when funds are received. Debit/credit card transactions are often not well-suited for larger payments, and payment functionality is restricted (to blocking funds and capturing funds) allowing for one-time payments as well as enabling future processing of payments – however with no guarantees with respect to the terms of payment.

Using CBDC programmability, payment schemes can be encoded and agreed to by various involved parties, allowing for no more (or less) to be transferred between the parties, and if required upon any stipulated rules encoding within the agreement. Such a system would allow for payment schemes to be automated removing possibilities of manual processing errors whilst ensuring all parties' interests are upheld (according to the encoded logic).

More so, to avoid manual verification that a payment has been received so that a process can begin, e.g. manufacturing of a product, a programmable CBDC solution could allow for a merchant's system to automatically initiate associated processes and thus reduce costs. This could be achieved through the provision of an interface, whether passive or active, allowing for external systems to either check or subscribe for an update in relation to a payment, or the CBDC system could actively alert the merchant. Indeed, this brings to light issues regarding interfacing/interoperability with external systems, not from the point of view of interoperability with other CBDC/DLT/Cryptocurrency-based systems, but with other stakeholders' digital systems. Issues pertaining to programmability and interfacing with such systems will be discussed below.

Programmability Required:

A **parameter/template interface** that allows for involved parties themselves, or banks (OBO parties) to enter into such payment terms.

Such standard parameter/template interfaces required above can be designed by various stakeholders including merchants and banks using a **DSL or visualisation tool** and/or potentially other players through the use of a **smart contract-like language.**

DeFi – Decentralised Finance

Decentralised Finance (DeFi) has emerged within the Crypto-space to provide an alternative to centralised finance business models, allowing for similar facilities and operations to be offered from a decentralised network – which may be a suitable alternative for such operations where trust in the centralised service provider is questionable.

For example, Ethereum's public blockchain network runs a fast-growing number of self-executing contracts, including algorithmic protocols for lending and borrowing assets (e.g. Compound), future markets (e.g. Augur), and decentralized exchanges (e.g. Uniswap). These and several other contracts that run on Ethereum today control billions of EUR worth of digital assets.

Blockchain and DLT are often seen to provide a solution to decentralising all trusted parties and only all trusted parties, however, this is not the case. Blockchain and DLT provide a solution to eliminating those trusted parties that are ideally removed/untrustworthy, other existing trusted parties need not be removed if the stakeholders have trust in that party. Similarly, DeFi-like solutions could be provided where certain trusted parties or certain operations of trusted parties could be delegated to a DLT, and those operations which stakeholders would trust to be executed by trusted entities may remain centralised. Furthermore, if a CBDC were to be implemented using centralised systems (that the CBDC and various other trusted stakeholders may have various forms of control over), decentralised-like finance operations could be provided to users/consumers which provide similar functionality to typical Crypto DeFi applications. The difference is that users must trust the technology platform which allows for such smart contract-like behaviour to execute. Furthermore, with such a system safeguards could be put into place allowing for CBDC management/operators or other authorities to intervene to some extent if required – for example, if a bug exists in code, or if someone's account is hacked. The level of intervention, and the system in general, can be designed to meet the different levels of intervention as required. The question is more a policy-related one in which it must be decided how much control centralised management/operators have (which may impact the trust that users would have in the system).

Programmability Required:

A **parameter/template interface** that allows for involved parties themselves, or banks (obo parties) to enter into such agreements.

Such standard parameter/template interfaces above can be designed by CBDCs/Banks and/or potentially other players through the use of a **smart contract-like language or a DSL**.

Custodianship Services

A common saying in the cryptocurrency community is “Not your keys, not your crypto” – this saying highlights the importance that controlling the keys to a particular digital wallet ultimately implies control of the assets stored within. As an example, consider when users store their cryptocurrency at an exchange and are able to access/transfer their funds by logging into the respective exchange. In actual fact, it is the exchange that has control of the underlying cryptocurrency assets and who follow their clients’ instructions to undertake transfers. If the exchange was to go bankrupt or lose access to all the underlying digital assets, then the consumers would not be able to directly transfer their funds out – since they do not have access to the underlying keys that control the cryptocurrency assets. Also, it is important to highlight that for use-cases where end-users store and use their own keys, if they were to lose the keys, then they would not be able to get access to their funds.

As a side-note, the following discussion is important in this context: CBDCs could be designed in a myriad of ways that enable for a spectrum from: (i) end-users have exclusive full-control of their keys (and if their keys are lost, then funds would also be lost); to (ii) end-users have control of keys whilst CBDC maintaining operators would have some rights to override/reset/intervene where required; to (iii) end-users do not use keys but typical internet/mobile banking interfaces and credentials. Now, indeed the level of control/decentralisation that the system will support is dependent on the policy and design goals of the system.

The discussion and perils of losing one’s keys goes beyond just such direct loss of access. It brings with it issues of inheritance. If someone passes away and does not pass on their keys, then all funds associated would be lost.

The important note to highlight here though is that there exists a class of users that prefers to keep control of their keys, whilst there is another class of users that would prefer to use custodianship services to get access to their cryptocurrency. Indeed, such services are being investigated within the decentralised cryptocurrency landscape.

CBDCs could provide a custodianship service for users who want to store their other non-CBDC decentralised cryptocurrency in a manner that can be managed through a trusted entity like a Central Bank, Bank or other operating entity. CBDCs with programmability features could allow for custodianship services to be provided by CBDCs for the non-CBDC ‘traditional’ decentralised cryptocurrencies. Central banks, and banks are in a unique position to be able to offer such services, where CBDC-enabled programmable smart contracts could offer assurances that an end-user can get transfer their cryptocurrency out to their wallets (outside of the CBDCs), whilst also offering assurances that if such services falter, then CBDC programmability could be written to automatically compensate clients for any loses. Through Central Banks, consumers would be able to build assurances that they can store they non-CBDC cryptocurrency with guarantees that CBDCs and nations can provide. Indeed, end-users in this case must have trust in the CBDC, governing structures, and jurisdictional frameworks – just how citizens currently trust central banks.

Not only could CBDCs be providing such services, which would bring “traditional” cryptocurrency and CBDCs closer together, but custodianship services along with DeFi (mentioned above in use-case 5) could open the door for many new types of Centralised-Decentralised Finance applications, allowing for existing risks in the “traditional” DeFi space to be counteracted through centralised assurances.

Programmability Required:

A **parameter/template interface** that allows for involved parties themselves, or banks (obo parties) to access "traditional" cryptocurrency funds that are under the custodianship of CBDCs would be required.

Such standard parameter/template interfaces above can be designed by CBDCs/Banks and/or potentially other players through the use of a **smart contract-like language or a DSL**.

Non-Fungible Tokens and Real-world Assets

Use-case 6 above describes custodianship services that CBDCs could offer with respect to "traditional" decentralised cryptocurrencies. Yet, banks currently nowadays provide similar services and require similar arrangements for management of not only financial assets of its stakeholders, but also physical assets. For example, banks may often consider guarantees provided in the form of physical assets (such as property, paintings, diamonds or any other physical asset). Non-fungible Tokens (NFTs), i.e. tokens that are unique in nature, are often used to represent real-world assets, e.g. such as paintings, diamonds (and even property). Once laws recognise that ownership of virtual tokens represent ownership of the real-world asset they represent, then CBDCs could manage such real-world assets for consumers. More so, digital agreements could be entered where the real-world assets provide any guarantees required by only agreeing to digital terms of the agreement and giving the agreement access to control the tokens accordingly. This is just the tip of the iceberg, consider any use-cases that Central Banks and Banks require knowledge and/or guarantees and/or interest based upon real-world assets – all these use-cases could be automated with minimal overhead, whilst ensuring that processes are followed and not tampered with.

Programmability Required:

A **parameter/template interface** that allows for involved parties themselves, or banks (obo parties) to enter into any such digital agreements concerning NFTs or real-world assets.

Such standard parameter/template interfaces above can be designed by CBDCs/Banks and/or potentially other players through the use of a **smart contract-like language or a DSL**.

CBDCs and the Oracle Problem

The oracle problem describes how blockchain and DLT systems in isolation do nothing more than keep track of ownership of resources and ensure that the data and digital processes encoded within them operate according to the pre-defined rules. To affect beyond this, blockchain and DLTs must interact with the outside world. Blockchain and DLT systems, however, do not actively interact with the outside world but rely on external parties (often referred to as Oracles) to initiate interaction. Indeed, the programmability of Blockchain systems becomes more useful when they can interact with systems outside of their own network. For instance, insurance providers can implement automated flight insurance claims disbursement on smart contracts. The blockchain would need to interact with an external system to get accurate flight schedule data and their actual departure times. If the expected result is to settle payments using traditional systems, it again requires the ability to interact with such external systems to securely perform the transaction. A digital euro, as a system relying on trusted entities for this operation, "mitigates" the problems described above simply: As appointed entities are entrusted with verifying transactions, they can also provide information that is not native to the CBDC system. This solution of course is not without its trade-offs (Chainlink, 2020). Recent research however, showcases how blockchain systems could directly make calls to external web services potentially mitigating, to an extent, their reliance on oracles (Ellul and Pace, 2021).

Programmability and Execution on DLT vs RTGS

Whilst Bitcoin provided limited ability for programmability (through its Bitcoin Script), Ethereum was the first blockchain to introduce programmability that allowed for more complex processes to be encoded and executed in a blockchain through the introduction of smart contracts. Smart contracts are nothing more than code that executes on a DLT. The fact that the code executes on a DLT, though, implies that: (i) the code cannot be changed (if the DLT is immutable); (ii) the code is available for anyone who has access to the DLT to see; and (iii) data cannot be manipulated in any manner that the smart contract does not allow. As an example, consider two partners that opt to start a partnership/company together and decide that 50% of profits at the end of the year are sent directly to the account of partner A, and the other 50% are sent to the account of partner B – this could be implemented in a smart contract. The smart contract guarantees that neither partner could manipulate the data or process for their own benefit.

A DLT provides these guarantees and ensures that neither the data nor processes can be manipulated because there is no single computer/server or subset of computers that is storing associated data and executing the digital processes – but all computers in the DLT store and process data (indeed, scalability methods are being investigated such as sharding but let's ignore this for the scope of this discussion). Since, all nodes collectively are storing and executing the processes, any nodes that try to manipulate data or a process will be caught out, and their proposed changes will be ignored. So, DLT is providing guarantees through the technology that neither data nor processes can be tampered with. It is for this reason that DLTs provide a suitable platform to automate digital processes that are parts of agreements – because the code will do exactly what it was programmed to do. The above is equally applicable to PoA systems.

A CBDC deployed on a traditional infrastructure, such as Europe's RTGS would not be able to natively replicate the functionality of smart contracts. To mitigate this, there is the option on programmability by proxy. In such scenario, a digital euro would rely on a non-native system (permissioned or permissionless DLT, database, or otherwise) for its programmable functions with the results "fed" in TARGET/TIPS and ultimately settled in (digital) euro. Such applications of programmability by proxy have already been developed. Most recently, Deutsche Börse, Deutsche Bundesbank and Germany's Finance Agency successfully tested a framework that allowed for an electronic security deployed on permissioned DLT, to be settled in central bank money (Deutsche Börse, 2021).

To the extent that basic instructions can be translated between the two systems, there is nothing to suggest that schemes can't be devised to facilitate for more complex exchanges. In that sense a CBDC deployed on TARGET/TIPS could achieve complex programmability by proxy. Naturally, the question becomes one of resilience of intervening solutions, and of cost-benefit versus systems with native programmability.

Why Blockchain/DLT? Is Blockchain/DLT needed to achieve programmability?

Using more or less complex mechanisms including specialized or general-purpose programming languages, operators can instruct the system to execute specific operations when specific conditions are met, thus specializing the system to meet their specific needs. Not only this allows turning a general-purpose system into a specialized one, but this can typically be done, again and again, providing a way to evolve over time how the system functions.

In the case of blockchain technology, programmability plays a key role in allowing different applications to run on top of blockchain networks that otherwise do little more than connect various parties. This takes the form of programs that interact with the network activity and react to specific events in a predefined way aimed at achieving a specific goal. These programs are commonly referred to as "smart contracts" (even though they are neither smart nor contracts in the literal sense). Smart contracts have similarities with the stored procedures of traditional relational database systems. They are a set of instructions executed on the network in response to transactions submitted by a participant in the network. The actual function thus provided is application-specific and can vary in nature based on the type of blockchain platform being used. However, generally speaking, these programs are designed to ensure that the transactions submitted to the network are valid, both in terms of whether they contain the data required for the transaction to be processed successfully and in terms of whether the transaction is acceptable given the current state of the application.

SECTION 4.3 TRACEABILITY, COMPLIANCE KYC/AML

Anti-Money Laundering/Counter-Terrorist Financing (AML/CTF) regimes are the set of laws, rules, and regulations that countries adopt to mitigate the use of the financial system to launder proceeds of crime, engage in fraud and other illicit financial activity, finance terrorism, and evade sanctions. The European Union adopted six consecutive Directives between 1991 and 2020 to harmonize most aspects of AML/CTF requirements that have been globalized by the Financial Action Task Force (FATF), an intergovernmental body founded in 1989 by G7 countries to promote global adoption of regulatory standards that combat illicit financial activities. Although specific requirements can differ by country, AML/CTF regulations typically impose recordkeeping and reporting requirements on financial institutions, and basic obligations include customer identification and "know your customer" requirements (KYC), the so-called travel rule, and suspicious activity/transaction reports, that require disclosure of possible criminal activity to public authorities. These regulations turn financial intermediaries into "gatekeepers" responsible for preventing bad actors from gaining access to the financial system, and for providing information to assistant public authorities detect and disrupt their activities when they manage to circumvent these controls.

AML/CTF regimes are designed to address the risks posed by anonymous cash transactions and customer records maintained on private ledgers by financial intermediaries who have at times used customer confidentiality to frustrate law enforcement investigations by shielding complicity in -- or active indifference to -- their customers' illicit activity. Regulations typically adopt a risk-based approach that balances the risk of illicit financial activity with competing social values of privacy and financial inclusion. While cash transactions carry elevated illicit finance risks, regulations impose recordkeeping and reporting requirements on financial institutions to report cash transactions and suspected illegal activity rather than opting for prohibition, which would disproportionately affect those on the margins of the financial system. At the same time, these requirements implicitly impose tangible costs that further financial transparency but can adversely impact access to financial services. And the intangible costs to financial privacy of mandated third-party surveillance are not ignored, but they are limited to preventing its misuse by governments in connection with law enforcement investigations. Customer records are protected by statutory privacy rights, with an exception for reporting of suspected criminal activity to law enforcement authorities who can use this information to pursue leads but are otherwise prohibited from disclosing it.

Recent efforts by global regulators have focused on improving the effectiveness of current AML/CTF regimes, which face enormous challenges in preventing illicit financial activity. Banks and other traditional financial institutions spend enormous sums of money implementing transaction monitoring systems that typically generate false positives in excess of 90 percent and require armies of investigators to clear. Governments must then invest enormous resources on their own data analytic tools that unwind this noisy data to identify trends and leads which they use to detect and disrupt bad actors and illicit financial activity. Moreover, limited by legal restrictions, governments struggle to share information with financial institutions that would provide the context essential to generate high-value reporting. While public authorities in some jurisdictions have had some success addressing these issues through public-private partnerships that facilitate information sharing, these arrangements face clear limits to scalability.

The development of a digital euro presents a unique opportunity to address the inherent limitations of the current AML/CTF framework; however, its effectiveness - along with the required tradeoffs between financial transparency, consumer privacy, and financial inclusion - will depend on the particular design adopted. As described in Section 2.2, the final form of any digital euro will reflect two critical choices: first, whether it is implemented through a Centralist system in which individuals and entities hold accounts directly with central banks or a Federalist system in which commercial banks hold digital euros and issue commercial bank money to retail investors, much as they do today; and second whether it will be account based, or token-based and maintained on private ledgers or blockchain.

Account-based systems will ultimately face the same limitations to AML/CTF effectiveness and zero-sum tradeoffs that exist in the current financial system. On the one hand, a Federalist, account-based system would be most similar to the current system since it would mainly involve interbank transfers rather than retail transactions. Commercial banks would comply with existing AML obligations, and consumer privacy would be preserved through existing compliance controls and legal protections. While the effectiveness of traditional AML/CTF measures could be enhanced if a digital euro fully replaced cash, it would disproportionately impact underserved communities who routinely face difficulty maintaining banking relationships. On the other hand, a Centralist, account-based system could arguably achieve transaction transparency by eliminating financial intermediaries and creating a comprehensive ledger of all financial activity. Such an approach would require central banks to build customer onboarding, transaction monitoring, and customer support services that commercial banks have spent enormous time and resources developing. Even if feasible, a Centralist, account -based digital euro would create an inviting “honeypot” of information that would prove challenging - if not impossible - to protect from malicious actors, including intelligence agencies of hostile states and their proxies. Perhaps most importantly it would transform central banks into virtual “panopticons” undertaking mass surveillance on a scale that raises profound privacy concerns and results in potentially insurmountable legal and political impediments to adoption.

Unlike its account-based counterparts, a token-based digital euro - whether Centralist or Federalist - provides the potential to alter the zero-sum trade-off between financial integrity, privacy, and financial inclusion inherent in current AML/CTF regimes. Token-based systems based on distributed ledger technologies (DLTs), colloquially referred to as blockchains - a family of cryptographic protocols that have particular attributes uniquely suited to combating illicit financial activity. Since blockchains record transactions on an immutable, distributed ledger available to all network participants, the provenance of every transaction is traceable to its source, greatly facilitating the identification of illicit financial activity over traditional account-based systems which are only traceable through customer relationships. Blockchains offer a granular view of information to authorities who can cross-reference transaction data with confidential investigative and intelligence information to more effectively identify, disrupt and dismantle illicit financial networks.

In addition to traceability, newer smart contract-based blockchains enable the creation of “programmable money” that provides for conditional execution of transactions. While smart contracts are currently used to create automated escrow functions, liquidity pools, and other innovations in decentralized finance, they could be readily programmed to require satisfaction of regulatory requirements as well. For example, a digital euro could be programmed to prevent the execution of transactions with sanctioned parties, or automatically report transactions that meet certain regulatory criteria, such as monetary thresholds, association with “dark web” activity, and other red flags. A token-based digital euro permits financial transparency, previously dependent on financial institutions’ operational ability or willingness to implement effective controls, to be hardcoded into a blockchain protocol itself. In addition, advanced cryptographic techniques such as zero-knowledge proofs and fully homomorphic encryption can be layered on top of smart contract-based platforms to shield transaction history and data from unauthorized parties, rather than relying on privacy and security controls that have proven increasingly ineffective against data miner profiting from personal information or cyber-intrusions and ransomware attacks by malicious actors.

In sum, the programmable nature of DLTs permits a more nuanced and flexible balancing of AML/CFT requirements, privacy protections, and cybersecurity controls than currently possible. It would also permit a more efficient allocation of resources to combat illicit financial activity. Law enforcement authorities and regulators would no longer have to expend scarce resources ensuring regulatory compliance that would be better spent directly detecting, investigating, and preventing illicit financial activity. Governments would no longer have to spend constrained budgets re-analyzing noisy data and could instead redeploy their resources to directly analyzing blockchain data to more effectively detect illicit financial activity, prosecute illicit actors, forfeit illicit proceeds, and dismantle illicit financial networks. Arguably, some of the above functions could be encoded with proper automatic controls in existing systems too.

SECTION 4.4 FUND CUSTODY & USER EXPERIENCE

A token-based digital euro could also enable cash-like features that permit peer-to-peer transactions without the use of financial intermediaries. While DLTs can be designed to support custodial accounts with central banks (in a Centralist system) or commercial banks and other financial intermediaries (in a Federalist system), they inherently permit users to conduct peer-to-peer transactions much as they do with cash today. Blockchain protocols natively permit anyone with an Internet connection to use encryption algorithms built into the protocol to create a private key known only to them that generates a public address from which their private key cannot be reverse engineered. This allows public blockchain addresses to be shared with anyone without concern -- unlike, for example, a bank account number - allowing it to serve as a secure pseudonym for blockchain transactions. Once generated, users are responsible for securely preserving their own private keys, theft or loss of which results in permanent loss, making crypto assets a digital bearer instrument owned by a private key holder. As the technology has matured, third-party developers have created software applications known as wallets to securely hold public/private key pairs to help drive adoption by less sophisticated users, commonly referred to as self-hosted wallets. In addition, the rapid pace of innovation in DLTs has resulted in newer protocols that use minimal energy and computing resources and can operate on inexpensive mobile phones. A token-based digital euro developed on a mobile-first blockchain protocol could serve as digital cash for underserved communities that have access to mobile phones but not bank accounts.

Self-hosted wallets are commonly believed to carry a higher risk of illicit financial activity because, unlike custodial accounts which require financial intermediaries to maintain customer identifying information that can be provided to law enforcement, users transact through unhosted wallets revealing nothing more than their pseudonymous public address. From this perspective, personal crypto transactions seem to marry the benefits of cash with the convenience of electronic payment, but without either the physical constraints of the former or the risk controls imposed on the latter. Despite this, there is good reason to believe that the particular attributes of blockchain technology could reasonably mitigate the risks of self-hosted wallets. The inherent traceability of all blockchain transactions makes self-hosted wallets far less risky than anonymous cash transactions. Moreover, the ability to program regulatory requirements into the underlying blockchain protocols means that self-hosted wallet transactions would be subject to the same regulatory requirements as transactions conducted through custodial wallets. And financial institutions would be able to identify high risk self-hosted wallets based on their transaction history and subject high-risk wallets to enhanced controls. None of these mitigating measures are possible today with respect to cash transactions. While none of these measures completely eliminate the risk that unhosted wallets could be used to facilitate illicit financial activity, central banks should consider whether they sufficiently reduce illicit finance risk to a level that justifies their use to support the availability of a digital euro for underserved communities that find it difficult to establish banking relationships.

Chapter 5: Economic and Macroprudential Considerations for a Digital Euro

SECTION 5.1 IMPLICATIONS OF A DIGITAL EURO FOR FINANCIAL STABILITY

The introduction of a CBDC creates two main risks for financial stability, linked to two different scenarios. The first risk is that of financial disintermediation in calm times. The second risk is represented by the possibility of systemic bank runs in times of financial distress.

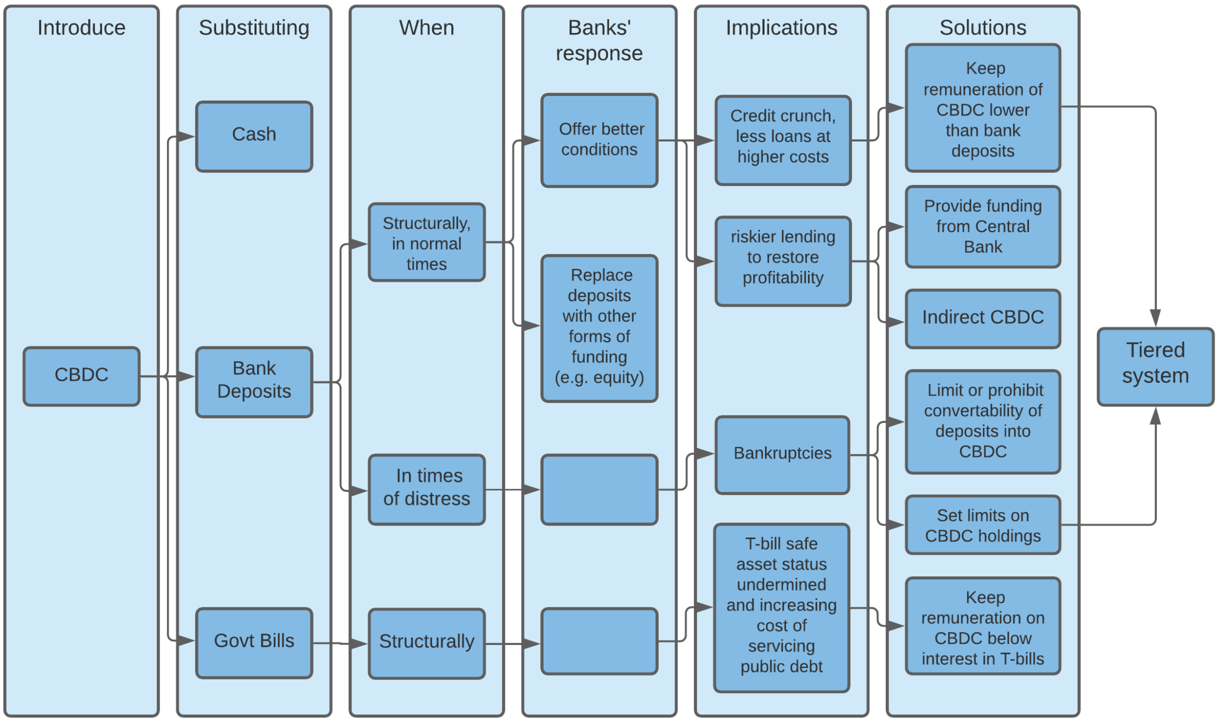

Figure 37 Financial stability risks Source: (EUBOF)

The risk of disintermediation

Explanation of the disintermediation process

The introduction of a CBDC may cause the withdrawal of funds from banks and their conversion into CBDC (see for example Carapella and Flemming, 2020, CPMI-MC 2018, Kim and Kwon 2019, Fernández-Villaverde et al. 2020a). This effect would be limited if households used CBDC mainly in substitution for physical cash. However, if commercial bank deposits were freely convertible into CBDC, households, and firms could be less willing to hold liquid money in the form of bank deposits and could prefer to hold CBDC instead. If this were the case, the substitution of bank deposits with CBDC would cause a loss of funding for commercial banks (Bindseil 2019) and a shrinking of the banking sector's balance sheet. This is precisely what "disintermediation" means (Bank of England 2020).

Therefore, the level of disintermediation caused by the introduction of CBDC is determined primarily by its substitutability with other forms of money. It is crucial to understand whether CBDC could be a substitute for cash, bank deposits, or both, and this, in turn, depends on the design features of CBDC (Bank for International Settlements 2020, Bank of England 2020, Claeys and Demertzis 2019).

Another very relevant factor in the disintermediation process is the behaviour of the central bank after a CBDC is introduced (Claeys and Demertzis 2019, Andolfatto 2018).

In the following, we assume that the design of a CBDC is such that it does cause disintermediation. Not only could disintermediation occur after a CBDC is first introduced, but central bank money and commercial banks' money could be "structurally" pitted against each other.

In other words, in normal times commercial banks would compete with the central bank to hold deposits. This effect would be reinforced if the central bank does not fill the funding gaps of commercial banks caused by disintermediation.

The consequences of a CBDC would be both on banks' liability side and on their asset side.

We can identify two main effects on the liability side.

First, banks could try to offer better conditions on their deposits, increasing deposit rates, to counter the conversion of bank money into CBDC (Mancini-Griffoli et al. 2018, Bank of England 2020). This would increase funding costs for banks and reduce their profit margin and seigniorage.

Second, banks may try to replace the deposits that are converted into CBDC with other types of funding, such as commercial paper, term deposits, bonds, and equity (Mancini-Griffoli et al. 2018, Bank of England 2020). This second option has three further implications:

1. funding would likely become more expensive,
2. funding may become less stable,
3. market discipline may decline if banks lose more uninsured than insured depositors. This could push banks to take on more risk (Mancini-Griffoli et al. 2018).

To sum up, if disintermediation is not adequately dealt with, it may cause an increase in the cost of banks' funding.

On the asset side, as a consequence of a higher cost of funding, banks would have to increase lending rates and transaction fees to maintain profitability. In the literature there is a variety of opinions on the overall effects of this process on lending activity. Many authors (see Fernandez-Villaverde et al. 2020a, Keister and Sanches 2019, Claeys and Demertzis 2019, Kim and Kwon 2019) envisage negative effects on lending activity by commercial banks. The effects on lending may also depend on banks' market power (Mancini-Griffoli et al. 2018). The greater this power is, the less loan demand decreases, and the more banks can preserve profits. On the contrary, banks with little market power are forced to shrink their balance sheets and reduce loans.

A very important variable in the disintermediation process is also the stance of the central bank. A relevant role is played by the spread between the interest rate on CBDC and on checkable deposits. If this spread is positive and too large, banks end up reducing their loans (Chiu et al. 2020).

Moreover, disintermediation and the ensuing reduction of lending can be avoided if the central bank steps in as a source of funding (see Andolfatto 2018, Brunnermeier and Niepelt 2019, Kim and Kwon 2019). If, instead, the central bank does not fill funding gaps of commercial banks, the competition between the two may leave space to lower credit creation by banks. Moreover, in a more extreme scenario, it may pave the way for a system of narrow banks (Claeys and Demertzis 2019, Gross and Siebenbrunner 2019) or even for the complete disappearance of banks' credit creation. In the latter case the central bank would directly create credit (as in the "sovereign money" approach described by Bindseil 2019).

It is important to highlight once again that in the previous explanation we have assumed that the design of a CBDC favours disintermediation. However, this cannot be taken for granted. Bofinger and Haas (2021) stress that "from a user perspective, the narrow solutions that are discussed by central banks so far do not seem attractive enough to compete successfully with private bank deposits and private retail payment systems like PayPal. The key advantage of CBDC, its absolute safety, is irrelevant for retail payments". Furthermore, from a historical point of view, there are examples where in calm times safe non-bank deposits coexist with bank deposits, even if the former have higher interest rates (Monnet et al. 2021).

The risk of bank runs

In times of financial distress, households and firms tend to convert their deposits into safe assets and cash, with possible ensuing bank runs. A CBDC, being a liability of the central bank, would have a higher degree of safety with respect to bank deposits. Therefore, in a situation of financial distress, it could facilitate bank runs in a digital form (see CPMI-MC 2018, Bank of England 2020, Fernandez-Villaverde et al. 2020b; see Monnet et al. 2021 for a historical perspective).

There is not full agreement on this issue in the literature. Some authors argue that a CBDC would allow runs towards the central bank with "unprecedented speed and scale" (CPMI-MC, 2018), while others think that "in many cases, this effect will be muted" (Mancini-Griffoli et al. 2018). In any case, the design of a CBDC plays a key role in this situation as well.

Moreover, in times of financial distress, a CBDC can also play an active role, providing to the central bank some useful instruments. In particular, it may facilitate the provision of liquidity to banks, helping to calm down bank runs (Mancini-Griffoli et al. 2018). The onset of a digital bank run may also act as a signal for the central bank to understand the conditions of the financial system and provide a fast and effective response (Keister and Monnet 2020).

Other financial stability and integrity issues

The biggest financial stability issues are disintermediation and the increased risk of bank runs. However, other minor questions related both to stability and integrity must not be overlooked.

The effects of CBDC on financial integrity depend on its design. Strict limits on the size of transactions, coupled with facilitation of identity authentication and tracking of payments and transfers would strengthen financial integrity. Moreover, if it is account-based, a CBDC could help prevent illicit payment and store of value with central bank money. On the other hand, a design that allows for full anonymity and large-value transactions would undermine financial integrity. Once again, we can see that the effects of a CBDC on the economy inevitably depend on its concrete design, which has to be planned according to policy preferences, without overlooking real-world impacts.

If the CBDC is designed in such a way as to preserve anonymity and hence facilitate cross-border payments, its adoption would greatly increase the volatility of international capital movements. Indeed, if we take into account the international environment, very large net cross-border movements of CBDC may not only complicate the conduct of monetary policy but also undermine financial stability. CBDC could, in some situations, lead to large capital movements, exchange rate disturbances and asset price volatility. The effects of cross-border CBDC movements would be especially pronounced during times of generalized flight to safety. Indeed, using a CBDC as an international currency could potentially enable faster deleveraging in capital markets, accelerating cross-border contagion and amplifying exchange rate fluctuations (CPMI-MC, 2018).

Solutions to financial stability risks

To contrast the risks of financial disintermediation, electronic bank runs and other potential threats to financial stability raised by the introduction of CBDCs, several solutions have been proposed. Some of them are not related specifically to CBDCs, but consist of more traditional measures (such as lender of last resort and deposit insurance). We shall therefore not discuss them here. Others, instead, involve specific design features of the CBDC and will be reviewed in turn in the following paragraphs:

1. lower remuneration of CBDC with respect to other policy rates (Pfister, 2020; Claeys and Demertzis, 2019);
2. limited convertibility of CBDC (Kumhof and Noone, 2018);
3. cooperation of the central bank with commercial banks in relation to the issuance of CBDCs (Claeys and Demertzis, 2019; Mancini-Griffoli et al., 2018; Brunnermeier and Niepelt, 2019);
4. control of CBDC volumes (Bindseil, 2019; Pfister, 2020; Gross and Siebenbrunner, 2019; Berentsen & Schar, 2018).

As we shall see, some of these features could allow CBDCs, not only to avoid weakening financial stability, but indeed to strengthen it (Kim and Kwon, 2019, p. 1).

Lower remuneration

Remunerating a retail CBDC could make it even more competitive with respect to bank deposits and government bonds. Therefore, it could end up reducing the quantity of bank lending to the economy and even interfering with the role of government debt as a safe asset.

Based on historical evidence concerning the switch from private bank deposits to government-backed deposits at savings banks (Caisses d'épargne ordinaires) in France in the interwar period, Monnet et al. (2021) argue that "it would be possible for CBDC to pay higher interest rates on deposits in normal times, as long as there is a deposit ceiling that also prevents runs in uncertain times." Users could be prepared to accept a lower remuneration on money held with private institutions, because of the variety of additional services offered by the latter (such as credit, portfolio management, advice). However, most authors agree that remuneration on CBDC should be set in a way that avoids adverse effects on financial stability:

- Remunerating CBDC at a slightly lower rate than the one paid on excess reserves would help prevent excessive competition with commercial banks (Pfister, 2020) and reduce *ex-ante* the incentive to use CBDC as a main store of value (Claeys and Demertzis, 2019).
- Even negative interest rates could be applied to reduce the attractiveness of CBDC with respect to bank deposits (Gross & Siebenbrunner, 2019). However, this strategy is unlikely to succeed when economic agents seek safety at any price, i.e., during systemic financial stress. Alternatively, this strategy may succeed, but at a cost.

  Even if it has been ruled out at the moment by the ECB, it is worth noting that the substitution of physical cash with CBDC would allow overcoming the zero lower bound on interest rates, with positive implications on monetary and macroeconomic stability, and hence, indirectly, also on financial stability. The possibility of driving interest rates below zero, through a negative remuneration on cash, would allow the central bank to be more effective in contrasting deflationary pressures and in sustaining investments (Rogoff 2014: 3), without resorting to other non-conventional monetary policies, such as quantitative easing, which might have the side-effect of increasing financial instability by fueling asset-price bubbles (Bordo and Levin 2017: 13).

- Moreover, remuneration should be set consistently with interest rates on government debt. If CBDC has a higher rate of return than public debt, it could undermine its role as a safe asset. Therefore, the CBDC interest rate should be lower than the one on government bonds.

Limited convertibility of CBDC

Some scholars think that limited convertibility of CBDC with other assets could prove effective in countering financial stability risks.

- The “light” approach is to discourage convertibility from bank deposits to CBDC through fees (Mancini-Griffoli et al., 2018; Pfister, 2020).

- The “hard” approach is to break the link between CBDC and other forms of money. CBDC and reserves would be distinct, and not convertible into each other. Moreover, there would be no guaranteed, on-demand convertibility of bank deposits into CBDC at commercial banks to avoid a flight to CBDC. An appendix to such a system would be the possibility for the central bank to issue CBDC only against eligible securities (Kumhof and Noone, 2018).

However, in this way core principles of banking and central banking relating to convertibility would be put into question. The convertibility of a kind of central bank money (i.e., CBDC) into other forms of central bank money (i.e., reserves) or private money (i.e., bank deposits) would be put into question, potentially undermining parity and introducing arbitrage opportunities. This would be a major change to the rules of the current monetary system, which does not seem fully justified and could create bigger risks than the ones it solves.

Cooperation of the central bank with commercial banks

Another proposed solution to the disintermediation issue is an enhanced collaboration of the central bank with commercial banks.

- The central bank could structurally provide more funding to commercial banks to replace the lost deposits (Claeys and Demertzis, 2019; Kim and Kwon, 2019).

  - A solution is envisaged by Brunnermeier & Niepelt (2019) who propose to substitute household deposits with central bank deposits at commercial banks, as backing for loans. Based on a monetary general equilibrium model, Kim and Kwon (2019) show that, if the central bank lends to commercial banks all the money that is withdrawn by households and converted into CBDC, then there is indeed an increase in private credit, since CBDC does not require reserves, and hence reserve-deposit ratio falls and nominal interest rates decrease, thereby increasing financial stability (pp. 23-24).

  - A slightly different solution is envisaged to address specifically the risk of bank runs. In this case, the central bank does not lend money systematically to commercial banks, to make up for their loss of deposits, but intervenes only in case of major withdrawals as lender of last resort (Gross and Schiller 2020). This would provide an effective instrument not only for crisis management in the event of bank runs, but also for crisis prevention since the expectation of central bank intervention would strengthen trust in private commercial banks.

- An alternative solution is the creation of an indirect CBDC, instead of a direct one. The central bank would not provide CBDC directly, but indirectly. This would take place through full-reserve banks or through "normal" banks that would fully back their CBDC liabilities with CBDC assets towards the central bank. However, such a solution would not allow one of the main innovations of a CBDC, i.e., building a strong, direct link between the central bank and the public.

Controlling CBDC volumes

Additional solutions are related to some form of control of CBDC holdings.

- The central bank could step in and set maximum limits on CBDC holdings (Mancini-Griffoli et al., 2018; Pfister, 2020). Gross & Siebenbrunner (2019) claim that limits on holdings and transaction volumes of CBDC could help prevent digital bank runs. The claim is also supported by empirical evidence related to the bank runs in France in the early 1930s, which were precipitated by the removal of ceilings on deposits covered by State guarantees (Monnet et al., 2021).

- The most elaborate proposal comes from Bindseil (2019), who advocates a two-tier remuneration system for CBDC. In such a system a relatively attractive remuneration rate is applied up to some quantitative ceiling (tier one), while a lower interest rate is applied for amounts beyond the threshold (tier two).

  Advantages would be multiple.

  - First, the payment function would be promoted by tier-one CBDC and the store of value function by tier-two. Thus, hoarding could be discouraged by adjusting interest rates. Then, such technology would ensure that CBDC is attractive for all households, as there is never the need to disincentivize tier-one CBDC by a particularly low remuneration rate.

  - A two-tier system would also allow better steering of the amount of CBDC, not through direct control of issued quantities, but by use of different combinations of remuneration.

  - Moreover, the central bank could provide a commitment with regard to the quantity of tier-one CBDC. For example, it could promise to always provide a tier-one quota of 3,500 euros to each citizen of the euro area. This amount would work as a safe pocket of digital money for everyone.

- Finally, Bindseil's proposal has also political implications. A two-tier system reduces the scope for popular criticism of the central bank, if the central bank promises to never charge negative interest rates on tier-one CBDC and clearly communicates in advance that remuneration of tier-two CBDC is not meant to be attractive.

Nevertheless, there could be some shortcomings.

- CBDC volumes could fluctuate as a consequence of rate spreads.
- There is a potential risk of bank disintermediation also with low-volume CBDC. Users may shift to central bank accounts and non-bank financial services and no longer have any bank deposit account. This will also depend on the differences between the regulatory treatment of commercial banks and other financial intermediaries. Anyway, a two-tier remuneration system would make the change less rapid and disruptive.

In conclusion, the tiered system would work better than other solutions, also because central banks have big experience with tiered remuneration systems, which could be readily applied to account-like CBDC. The central bank could set the remuneration of tiered CBDC to make CBDC both attractive and controllable and could resort to other solutions if the tiered system proves insufficient to avoid financial disintermediation and bank runs.

Monetary Section 5.2: Options for Monetary Policy

Monetary policy refers to actions and communications by the central bank of a given country that aim to manage the money supply (monetary mass or, equivalently, the main interest rate). In different countries, this management fulfils somewhat different mandates. For example, in the US the Federal Reserve has three objectives: maximum employment, stable prices (control of inflation), and moderate long-term interest rates (Federal Reserve, 2020). In Europe, on the other hand, the ECB sees price stability as the main objective from which economic growth and employment follow (ECB, 2019). This section introduces and discusses properties of a digital euro from the point of view of the above standard interpretation of monetary policy. At this early stage, however, the fact that the digital euro has not yet been fixed within the bounds of a specific monetary instrument blurs the boundary between monetary policy and suggestions for design requirements. In other words, the increasing awareness and relevance of a wide range of public and private electronic, digital, and blockchain-based currencies provide an opportunity to imagine, analyse, and discuss new and different properties of the medium of exchange that offer different and complementary ways to the current euro framework for fulfilling the ECB's monetary policy objectives.

The section starts with a very quick review of the main mechanisms of monetary policy, pointing out areas whose effectiveness seems to have decreased in recent years. It then presents possible ways in which a CBDC can perform similar or complementary monetary policy functions. The most important of these, which could also be regarded as a high-level *economic requirement*, is the contribution that a CBDC can make to *green inclusive sustainable growth*, *social inclusion,* and *social sustainability*. Somewhat counter-intuitively, we are arguing that social and environmental values can support economic value through **collaborative finance**, to which a CBDC is very well-positioned to contribute. The second part of the section, therefore, discusses how the increased interoperability of a DLT-based CBDC is uniquely placed to enable two examples of collaborative-finance applications in support of monetary policy objectives that operate at different geographical scales: obligation-clearing for the trade credit market at any scale, and mutual credit for communities at the local scale.

Standard Monetary Policy Levers

In the US Federal Reserve system, the Fed Funds *Target* Rate is the main lever by which the money supply and, indirectly, inflation is controlled. The Fed Funds *Effective* Rate is the (average) interest rate banks charge each other in overnight reserve loans. The Fed pushes this short-term rate up or down towards the target rate through open-market operations (OMOs), e.g. selling or buying treasury bonds, respectively. Selling bonds increases their supply in capital markets, causing their price to decrease; their coupon (associated interest rate) will therefore increase as a market response. The higher effective rate that results ('tight policy') makes loans more expensive and therefore less likely, which means that less money will be created by commercial

Interest Rates for Monetary Policy	**USD**	**EUR**	**GBP**
*Rate **set**/**measured** by central bank at which banks lend to each other*	**Fed Funds Target/Effective Rate** (Controls inflation, drives all other rates) [overnight loans] {Market-set, but controlled by OMOs} <Lowest>	EONIA, **€STR**	LIBOR, **SONIA**
Rate charged by central bank to banks for 1-day loans	**Discount Rate (Window)** (Lender or last resort) [usually overnight] {Fed-set} <Medium, varies between banks>	**Standing Facilities** (refi rate)	**Official Bank Rate** (used to be repo rate)
Rate charged by commercial banks to their best corporate customers	**Prime Rate** [short-term, but > 1 day] {Market-set} <Highest> -----►	(same) -----►	(same)
Rates charged by commercial banks for personal loans, mortgages, trade credit, etc.	**Lending Rates** [a few days to 30 years] {Market-set} <Much higher than the prime rate> -----►	(same) -----►	(same)

Figure 38 Interest rates for monetary policy Source: (EUBOF)

banks. The lower rate that results from buying bonds ('loose policy') has the opposite effect. Outside the US there are other rates for interbank loans, such as EONIA (ECB, 2021) in the Eurozone and the LIBOR (Kiff, 2018), which concerns banks in the UK, US, Canada, and Switzerland. Both EONIA and LIBOR are being phased out and replaced with more reliable and lower-risk indices: €STR (ECB, 2019) and SONIA (Bank of England, 2020b) respectively. The figure below shows a table summary of how the Fed Funds Rate and analogous indices relate to the main interest rates for three representative currency areas.

After the last banking crisis, when credit dried up, the main central banks lowered the target rate near zero. Since the financial crisis was deemed too severe to respond to a low interest rate alone, quantitative easing (QE) was also used, i.e. the purchase by the central bank of a wider range of financial assets, including corporate paper as well as long-term treasury bonds. When a liquidity crisis is deeper yet and banks are unable to borrow from each other, the central bank acts as a lender of last resort at a somewhat higher rate: the Discount Rate in the US, Standing Facilities or refi rate in Europe, and the Official Bank Rate in the UK. During the current Covid-induced negative supply shock, much larger amounts of QE than for the financial crisis have been deployed by the FED, ECB, and Bank of England. In addition, in several countries, the treasury sent cheques directly to citizens to stimulate demand, generally known as 'helicopter money' (Friedman, 1969), and/or set up various schemes to support firms who had put their employees on furlough due to the lockdowns.

As discussed in some detail by (Simmons et al., 2021), QE has been less effective than we all would wish, mainly because the incentive structure of financial markets makes it unlikely for the new reserves (generated in the bank accounts of the primary dealers when they sell treasury bonds to the central bank) to reach the real economy. One of the consequences of the QE funds remaining in the financial economy is the emergence of asset bubbles (e.g. real estate), which in turn fuel rising inequality. In other words, the QE monetary stimulus transmission channel appears to be broken or, at the very least, far from optimal.

At the same time, one of the unintended consequences of the Basel III accords, reached after the last financial crisis and aiming to decrease risk for pension funds and small savers, has been to make it much more difficult and expensive for SMEs to access trade credit from banks. In Europe, an instrument that partially addresses this problem is Targeted Long-Term Refinancing Operations (TLTROs), whereby banks receive very favourable terms on ECB loans if they, in turn, issue loans to companies in the real economy (for example for trade credit) – hence 'targeted'. With the ECB rate dipping below zero, however, it has become a rather expensive instrument since banks receiving these loans are getting *paid* at the current negative interest rate. And banks that have reserves at the ECB have to *pay* the ECB to keep them there! More controversially, the banks receiving the TLTROs and associated cashflows tend to be from southern Europe, whereas the banks with excess reserves tend to be from northern Europe. Due to space restrictions, we cannot give more than just a flavour of these basic concepts, levers, and instruments of monetary policy. The next section discusses possible ways in which a digital euro might be able to help.

Indicative CBDC-Specific Monetary Policy Instruments

Quite apart from the model that is adopted for the digital euro itself, for example, token-based or account-based (as discussed in much more detail in Section 2.2), one of its monetary policy uses could be as helicopter money to stimulate demand in pandemic-like situations. Another similar use could be as a channel for Universal Basic Income (UBI). A discussion of the appropriateness of such interventions or UBI as a citizen right is outside of the scope of this report. And yet, if the design of a CBDC could help support one or more of the standard mandates of central banks along with greater financial inclusion, for example for the unbanked, it seems safe to say that such a design would be welcome. Financial inclusion is one of the facets of social sustainability, by which we refer to a broad conception of the role of social value in all aspects of sustainability, as explained for example by UNRISD (UNRISD, 2014). The design and/or monetary policy tools discussed in this section focus on the social and economic dimensions of sustainability through instruments that have evolved over thousands of years specifically in support of real-economy markets (so similar in spirit to TLTROs). We are presenting (1) that the ideal of a strong market economy can be reconciled with the ideal of social sustainability through a shift in perspective that we refer to as 'collaborative finance'; and (2) the interoperability standards of a CBDC may make it uniquely positioned to enable and mediate this paradigm shift at the societal level.

The overriding mandate of the ECB is the control of inflation through stable prices, from which other desirables like employment are assumed to flow. Similarly, given that a CBDC design will already have to fulfil several requirements as a medium of exchange, it should probably concentrate on only one aspect of monetary policy, with the expectation that positive knock-on effects will propagate to the other mandates. In this section, we are suggesting that a CBDC, in addition to its cash-like function, is well-positioned to help strengthen the

productive economy. This impact could be achieved by integrating the CBDC with two examples of collaborative finance which, although they have both been around for a long time, reside on the fringes of the financial economy as it is understood today: obligation-clearing and mutual credit. The modern incarnations of both instruments depend fundamentally on a distributed software infrastructure accessible through the web or a phone. Both instruments combine some degree of decentralisation, which can be leveraged by blockchain architectures and protocols, with some degree of central control and management, which is consistent with a central bank perspective on the management of the money supply.

Obligation-clearing (Fleischman, Dini and Littera, 2020) is a very effective liquidity-saving mechanism (LSM) for providing relief in the trade credit market and, therefore, on the supply-side or productive part of the economy. LSMs such as clearinghouses and debt recovery services are a well-studied part of interbank payments, whose importance in payment and settlement systems is recognized in all 27 jurisdictions of the EU (Tompkins and Olivares, 2016). The opportunity to save liquidity is a consequence of the presence of queues in payment systems. In particular, when payments cannot be processed in the order in which they are queued, it makes sense to look at payment orders as a network of obligations. Such a network contains cycles that are the cause of liquidity shortage (gridlock) in sequential payment processing. In general, cyclical structures create situations in which several payments cannot be settled individually but can be settled simultaneously.

> An example of the clearing of a gridlocked cycle is provided by the well-known story of the travelling salesman who arrives in a town and stops at a hotel asking to take a look at a room before actually paying for it. The hotel manager agrees but asks for a $100 bill as a deposit. While the prospective guest is upstairs viewing the room the hotel manager runs across the street and hands over the bill to the shoe store owner, towards whom she had a debt. The shoe store owner takes the bill and goes upstairs to pay the dentist to whom he owed just such an amount. The dentist walks over to the hotel and hands the bill back to the manager to pay for a meal in the hotel restaurant from the night before that he had left on credit. Shortly thereafter, the travelling salesman comes back down and says that he is not interested in the room after all. The hotel manager returns the $100 bill and the salesman leaves. No net cash flow has entered the community but all the debts have been extinguished. Obligation-clearing is a much more sophisticated version of the same idea.

Because one of the main functional requirements of a CBDC is to be cash-like, even if it were never used for UBI it would still be a relevant instrument for the unbanked. Therefore, regardless of the fiduciary model (e.g. central bank vs. commercial bank accounts), the fact that a CBDC lowers the “bankability threshold” will create the illusion that the problems of the unbanked are solved. But at least one underlying problem will remain: unresolved gridlock situations will emerge sooner or later despite the presence of this new instrument: in other words, ownership of a CBDC account will not by itself make the unbankable bankable. However, because an obligation network is agnostic as to who the debtors and creditors are, it can be seen as a ‘blind leveller’ of large and small debts alike, independent of the socio-economic status of the debt holders. Such a network can be built easily as part of the CBDC system if the payments are allowed to be delayed. Some payments will need to be instantaneous, but others could be linked to electronic invoices at 30, 60 or 90 days. By recording them on a blockchain (or traditional) backend using publicly verifiable GDPR-compatible IDs, they will form an obligation network that can be cleared once a month in a given regional, national, or international jurisdiction, updating the amounts due accordingly.

The reason obligation-clearing is a form of collaborative finance is that it requires a network of creditors and debtors with a high level of mutual trust – needed for them to feel able to disclose their debts even if such data is protected by privacy regulations. From a microeconomic perspective, the very tangible benefit of the decrease in one's debt position breeds an appreciation for the other thousands of stakeholders who, by participating, are enabling this effect and for the system that implements it. The latter, in turn, leads to greater mutual trust between the citizens and the state, especially if tax obligations and the tax authority are included in the network. From a macroeconomic perspective, on the other hand, the pooling together of the debts of individuals and businesses is an example of collaborative finance at the level of a structural synergy between complementary sectors of the real economy that traditional finance does not provide. Individual citizens who invest in the stock market are "collaborating" with – usually large – listed enterprises rather than with SMEs. By contrast, the impact of obligation-clearing enabled by a unifying and interoperable CBDC-based framework will be most felt by the weakest individuals and SMEs. Finally, since no money is transferred in a clearing instance, there is no risk.

Having said that, as discussed in depth in (Fleischman, Dini and Littera, 2020), obligation-clearing can be "turbo-charged" with very small amounts of liquidity relative to the initial total debt of the network. This would give a clear role also to commercial banks as the custodians of one of the possible sources of liquidity, i.e. fiat. Figure 39 below shows a visualisation of how three liquidity sources could support an obligation network, using the same Sardex data analysed in detail in the same reference.

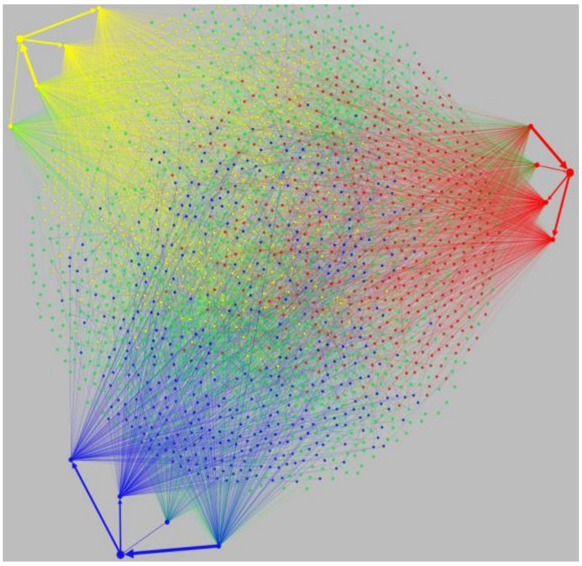

Figure 39 Visualisation of liquidity network
Source: (Fleischman, Dini and Littera, 2020)

In this picture, each node of the network is a firm or an individual. The arcs of the graph denote bilateral obligations (IOUs), not currency flow. The picture does not show all the obligations between these roughly 3000 points, it only shows the obligations that can be cleared with (red, blue, yellow) or without (green) the liquidity sources, thereby forming a so-called 'cyclic structure'. To utilise multiple liquidity sources the exchange rate to must be set to an agreed unit of account (e.g. the Euro) for each party at the moment of clearing, which is near-instantaneous. In this example, the three liquidity sources (larger nodes at the three vertices) each hold the accounts of 1/3 of the nodes (see Fleischman et al. for more details on the 4 nodes adjacent to each). Currency moves between accounts that reside within each of the three sources. Yellow could represent fiat held in bank accounts, red CBDC balances, and blue cryptocurrencies. A fourth source could be added representing mutual credit. Not all nodes will see their debt disappear, but all the nodes in this diagram will see their debt decrease.

Another way in which a CBDC could sustain the productive economy is through a policy that maximises the velocity of circulation, defined as the number of times the monetary mass circulates in a given period (or the number of times each unit of account is transacted, on average, in a given period). Normally it means ‘income velocity of circulation’ and is calculated as GDP/monetary mass (usually M1). In the context of a CBDC it makes sense to use the total transaction volume instead of GDP, obtaining with the units of measurement shown explicitly to demonstrate dimensional consistency. V is therefore measured in units of inverse time, i.e. it is analogous to a frequency (as a pure number ‘circulations’ is dimensionless). The monetary mass in the equation (Equation 1) is specifically the CBDC monetary mass.

$$V\left[\frac{circulations}{year}\right]=\frac{\text{Transaction Volume}\left[\frac{€}{year}\right]}{\text{Monetary Mass }[€]},$$

Equation 1 Income velocity of circulation Source: (EUBOF)

As Adam Smith noted long ago, the store of value function of money militates against the productive economy because it withdraws the medium of exchange from circulation. To maximise V in a CBDC context, therefore, a ‘demurrage’ tax or fee could be applied to positive balances after some time the account is idle, for example 1 year, to encourage spending. This function has been built into the Celo blockchain (cLabs Team, 2019) after the work of Silvio Gesell(Gesell, 1906). The units gathered through this fee could be set aside into a ‘community resilience fund’ that could serve to increase the impact of the green and just transition policies by increasing access while reducing overall risk.

A similar effect on V can be obtained with zero-interest mutual credit. As discussed by Graeber (Graeber, 2011) and many others, the earliest historical record of what today we call mutual credit goes back to the Babylonians approximately 5000 years ago, whereas coins were invented much later, about 2700 years ago in Lydia (in modern-day Turkey). In the modern era, aside from unsuccessful early experiments by Pierre-Joseph Proudhon and Robert Owen in the 19th Century, the earliest example of a mutual credit system is the Swiss WIR, which was set up in 1934 in response to the Great Depression as a B2B system between small Swiss companies. Another example, inspired by WIR[6], is the Sardex system (Littera et al., 2019). In the Sardex mutual credit circuit, the participating SMEs start with a zero-credits balance, and are assigned by the circuit manager a credit line that is approximately equal to 2% of their turnover. They also sign a contract to commit to selling their products and services (incl. renewable energy) for about 10% of their turnover, which is how they recover the debt they incur when their balance goes negative. Credits are created or issued whenever a balance goes negative and are destroyed when a negative balance receives a payment. Therefore, the sum of all the positive and negative balances in a mutual credit circuit is always identically zero. In mutual credit, the debtit and credit positions of any one member are not bilateral towards another member or the circuit manager, they are towards the circuit as a whole; this highlights the individual responsibility of the user towards the circuit – if the user’s balance is negative – and the collective responsibility of the circuit towards the user – if the user’s balance is positive. All positive and negative balances are at 0% interest, which stimulates spending and a higher V. Sardex credits are not convertible.

Whereas obligation-clearing is easily scalable to thousands or even millions of nodes, mutual credit tends to be very limited in its macroeconomic impact. Its strength lies elsewhere, namely in requiring – and reinforcing – trust-based relations between the members of a local circuit. Its local character tends to align well with cultural identity and environmental sustainability values, both of which reinforce the role of the commons in a given context. In other words, mutual credit reinforces precisely those aspects of an economy that pertain to social sustainability and green inclusive sustainable growth, whose effects tend to be most felt at small scales. In addition, however, even very small circuits would benefit from a national or pan-European obligation-clearing infrastructure (i.e. similar to a target for citizens and companies) and, by acting as liquidity sources, hundreds of circuits around Europe would amplify the macroeconomic impact of this instrument as well as provide greater financial inclusion for all.

From the foregoing, it should be increasingly clear that the standard that a CBDC represents for GDPR-compliant identity, transparency through a public blockchain, and payment method could act as a powerful integration engine for a series of very impactful collaborative finance initiatives and instruments that have been acting in isolation on the fringes of the financial economy. The ability of a CBDC to bridge the small-scale social values of mutual credit with pan-European obligation clearing – both operating in support of the real economy – furthermore, would partly balance the effect of QE on the financial economy (which, of course, also needs to be kept stable). Second, as briefly mentioned above, another example of integration is to give the ability to CBDC holders to delay their payments with a 'time to pay' (TTP) or maturity date, since any CBDC payment order that has not yet matured is an obligation and an IOU. Therefore, at the end of each month, a clearing run could be done for the multilateral set-off of not-yet-matured CBDC IOUs. Any positive balances would act as a liquidity source as before, along with any other sources, as discussed. An important constraint, however, is to disallow the sale to third parties of pre-TTP IOUs, otherwise the IOU themselves could become a separate currency or even a security. The CBDC must be designed to make the transfer of obligations impossible, otherwise we are back to square one.

A final variation on the theme could be to merge also some of the features of mutual credit with an obligation clearing-empowered CBDC. Rather than a form of UBC – for "Universal Basic Credit" – this feature could be made contingent on something similar to a credit score. This could be useful to lower the threshold not just of bankability but also of access to credit. The digital and/or blockchain nature of the CBDC would make it relatively straightforward to set up a smart contract that allows a small amount of credit based on a user's history and other relevant parameters, and that checks if the negative balance is recovered within the agreed or mandated time-frame. If so, with subsequent requests the amount of credit can be increased gradually, keeping track of a credit score that could eventually be used for a loan application with a bank. Such a feature could provide a "bridge" or "ladder" between individual citizens and the smallest of SMEs, to encourage personal entrepreneurship and greater self-reliance.

There are two challenges built into the CBDC-mutual credit integration suggestion. First, the CBDC would need to be account-based rather than token-based. This goes against the tradition of regarding money as a precious commodity, a perception reinforced by interest since it can be regarded as the price of money and increases its value over time. One of the reasons mutual credit is compatible with social sustainability is because at 0% interest it is a weak store of value, by design. Therefore, it functions well as a medium of exchange and as a unit of account pegged to the Euro (even if it's not convertible), properties that strengthen the real economy. But, more fundamentally, mutual credit also emphasises the sociological monetary theory perspective of money as a social relation of credit and debt, rather than as an asset. The reason it does so is because it is *created* as debt, and this is visible to all the users. Even if the social glue properties of the CBDC are deemed to be important enough to be designed into the currency, the account-based design choice will not be simple to navigate. The argument for 0% interest is a bit easier since it is supposed to be cash-like and the bonus of a greater velocity of circulation would help the real economy.

The second challenge is more difficult and also deep (Dini and Kioupkiolis, 2019). It relates to whether the central bank is prepared to accept the fact that the issuance of the CBDC could be in part distributed not simply to banks as with fiat in the current system, but to *individual natural and legal persons*. There are difficult aspects to be analysed relating to AML, KYC, and many other regulatory and accounting considerations, including convertibility. But given appropriate safeguards and limits, we feel that such an experiment is worth investigating further because it would represent a definite step forward in the democratisation of finance and the enfranchisement of the individual citizens. With such greater power would also come greater responsibility. A CBDC could therefore open up the possibility for an international and truly democratic conversation on the stability of the productive economy based on a much more sophisticated and universal financial literacy.

Chapter 6: Conclusions & Future Considerations

Central Bank Digital Currencies are the natural next step in the digitization of money and payment systems. Given the momentum and initiatives already underway worldwide, we cannot imagine a scenario where different forms of CBDCs do not co-exist with other forms of money in the near future.

Europe, as one of the world's largest and most innovative economies, is an important contender in the race to design, implement and deploy the digital money of the future. The European Central Bank is leading this effort as part of its mission to keep prices stable in the euro area and contribute to the safety and soundness of the European banking system.

This report aims at contributing to the ongoing debate to develop the digital euro by providing a foundational understanding of CBDCs, outlining the boundaries of the design space for the digital euro, as well as placing alternative design scenarios under the examining lenses of technological, economic, and usage-related considerations.

An ECB-issued digital euro would go a long way toward facilitating payments efficiency and security across the eurozone, furthering financial inclusion, and futureproofing the euro against developments in other economic jurisdictions (e.g. the USA and China) and non-sovereign implementations of private or decentralized forms of digital money (e.g. Diem or cryptocurrencies). The speed of innovation by other actors is relentless and a global race to define the world's reserve currency of the digital era is well underway. Europe cannot afford to not be part of this effort, by both closely monitoring global developments and innovating across dimensions specific to the idiosyncrasies of the eurozone.

Both the ECB and the European Commission have been active participants in the European and global debates, most recently through the ECB's *Report on a Digital Euro* (October 2020) and the EC's *Markets in Crypto Assets* (MiCA) proposed regulation (September 2020). Industry has also voiced their own opinions and comments, most notably through the very successful public consultation on ECB's report, which attracted a record number of 8,000+ responses by citizens, businesses, and institutions alike.

This report goes a step further from previous efforts to consider several design options for the digital euro and evaluate them against the core principles, scenario-specific requirements and general requirements posed by the ECB. We have outlined three dimensions of designing the digital euro, each having two broadly different design approaches:

- the **underlying technological infrastructure**, which can be either based on existing payment rails, e.g. TIPS, or built atop new technological architectures, e.g. blockchain,
- the **user access method**, which can be either account-based, i.e. more akin to the existing banking system functionality, or token-based, i.e. more akin to the existing experience of dealing with cash, and
- the **management** of both the technological infrastructure and distribution method of the new currency, which can be either centralist, i.e. controlled exclusively by the ECB, or federalist, i.e. facilitated through collaboration of the ECB with the private sector.

Naturally, the eight design combinations that result from this design space are not exhaustive of the numerous details and technicalities of the ultimate final design choices. However, they provide a useful compass for navigating the complexity of the space and allowing decision-makers to structure their debate on the relative advantages and disadvantages of each design option.

To facilitate this debate, we have proceeded to map each of the eight design options we have identified against the requirements for a digital euro, as outlined by the ECB. Further, we have addressed several additional considerations related to technology (interoperability and programmability features of the digital euro), regulatory aspects (traceability, compliance, and AML/KYC enforcement) and end-user experience (fund custody, digital wallet design and user interfaces). While exhausting the debate on these considerations goes beyond the scope of this report, we believe that addressing them will influence and be influenced by the core design considerations.

Finally, we have identified and studied several implications of the digital euro to areas such as financial stability or the operation of the European banking industry. For example, issuing digital cash directly to citizens and business by the European Central Bank would go some way toward disintermediating the existing commercial banking system and providing euro holders with a potential way to bypass private financial institutions in the event of financial crises or panics, thereby exacerbating the risk of bank runs. We have discussed such implications and offered potential solutions that feed back to the design of the digital euro, including remuneration policies, supply and convertibility of the digital euro, as well as possible collaborations between the ECB and commercial banks. Such implications, and associated policy recommendations, are naturally quite complex and each of them might be the object of a whole separate report. We have included them in the report for the sake of completeness and ensuring that decision-makers have a holistic overview of the design space and intricate interdependencies between technological, regulatory, policy, and usage options associated with the digital euro.

We remain confident that Europe will continue to pioneer global efforts to develop future-proof monetary instruments relevant to the digital era. Regardless of its exact implementation details, a digital euro will certainly go a long way toward safeguarding the stability and future prosperity of the eurozone, while at the same time respecting fundamental rights of European citizens and businesses, including privacy, due process and freedom of movement.

Notes:

1. This definition is largely consistent with the one provided in the World Economic Forum's whitepaper on "(Federal Reserve, 2020)".
2. A number of blockchain networks (including Celo, Polkadot, Cosmos, and Chainlink) are working to improve the data efficiency of trustless bridges. Additionally, Larsen notes that "[r]elay chain architectures work best with chains that have certain characteristics," suggesting that standardization in this area could help improve the overall performance and viability of this option.
3. It should be noted that the relevant text for these two categories is nearly identical in both publications. Although neither publication references the other, it is assumed that Larsen's report is the original source, as it was published in December 2018, while the World Economic Report came out in April 2020.
4. For a more detailed description of these issues, please refer to Matthew Hammond's blogpost on "Atomic Swaps".
5. Larsen makes this point himself, specifically noting that "[e]xchanging digital assets can mean a number of things, so let's call it the ability to transfer and exchange assets originating from different blockchains, **without trusted intermediaries (e.g. centralized exchanges)**. [emphasis added]
6. https://www.wir.ch/, since 2004 WIR Bank. WIR is short for 'Wirtschaftsring' or 'economic circle' but also the 'we' personal pronoun in German.
7. The debate on the specifics of money creation is ongoing. In a recent special report on banking by *The Economist* the fractional reserve theory of banking is cited repeatedly (*The Economist*, 2021), despite it having been discredited by both academic and central bank economists in recent years (Werner, 2014; Borio, 2019; McLeay et al., 2014). For the purposes of the present report, we note the potential effects and invite future research on the topic.

Bibliography

ABC (2012) *Farmers mourn death of French proto-internet - ABC News*. Available at: https://www.abc.net.au/news/2012-06-29/french-internet-precursor-shuts-down/4099492 (Accessed: 17 May 2021).

ACI Worldwide (2020) *COVID-19 Crisis Drives Changes in eCommerce Purchasing Behaviors, ACI Worldwide Research Reveals | ACI Worldwide, Inc.* Available at: https://investor.aciworldwide.com/news-releases/news-release-details/covid-19-crisis-drives-changes-ecommerce-purchasing-behaviors (Accessed: 16 May 2021).

Adrian, T. and Mancini-Griffoli, T. (2019) *The rise of digital money*. Washington, DC: International Monetary Fund. Available at: https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=2223231 (Accessed: 31 May 2021).

Adyen (2021) *Retail in the time of coronavirus*, *Adyen*. Available at: http://www.adyen.com/knowledge-hub/guides/covid-19/retail-in-the-time-of-coronavirus-1 (Accessed: 16 May 2021).

Areddy, J. T. (2021) 'China Creates Its Own Digital Currency, a First for Major Economy', *Wall Street Journal*, 5 April. Available at: https://www.wsj.com/articles/china-creates-its-own-digital-currency-a-first-for-major-economy-11617634118 (Accessed: 16 May 2021).

Asli Demirgüç-Kunt *et al.* (2017) *The Global Findex database*. Available at: https://globalfindex.worldbank.org/.

Auer, R. and Boehme, R. (2020) 'The technology of retail central bank digital currency'. Available at: https://www.bis.org/publ/qtrpdf/r_qt2003j.htm (Accessed: 14 May 2021).

Auer, R., Cornelli, G. and Frost, J. (2020) 'Rise of the central bank digital currencies: drivers, approaches and technologies', p. 44.

Bank of Canada (2017) *Project Jasper: A Canadian Experiment with Distributed Ledger Technology or Domestic Interbank Payments Settlement*.

Bank of Canada (2019) *JASPER–UBIN DESIGN PAPER Enabling Cross-Border High Value Transfer Using Distributed Ledger Technologies*.

Bank of England (2020a) 'Discussion Paper - Central Bank Digital Currency: Opportunities, challenges and design', p. 57.

Bank of England (2020b) *SONIA interest rate benchmark*. Available at: http://www.bankofengland.co.uk/markets/sonia-benchmark (Accessed: 17 May 2021).

Bank of England (2021) *Bank of England statement on Central Bank Digital Currency*. Available at: http://www.bankofengland.co.uk/news/2021/april/bank-of-england-statement-on-central-bank-digital-currency (Accessed: 16 May 2021).

Bank of Japan (2020) *The Bank of Japan's Approach to Central Bank Digital Currency : 日本銀行 Bank of Japan*. Available at: https://www.boj.or.jp/en/announcements/release_2020/rel201009e.htm/ (Accessed: 16 May 2021).

Bank of Russia (2021) *Bank of Russia presents Digital Ruble Concept | Bank of Russia*. Available at: https://cbr.ru/eng/press/event/?id=9739 (Accessed: 16 May 2021).

Bank of Thailand (2021) 'Project Inthanon-LionRock', p. 90.

Bellens, J., Lloyd, J. and Hamish, T. (2020) *Why the potential end of cash is about more than money | EY - Global*. Available at: https://www.ey.com/en_gl/banking-capital-markets/why-the-potential-end-of-cash-is-about-more-than-money (Accessed: 16 May 2021).

Bharathan, V. (2021) *DXCD, The Eastern Caribbean Central Bank Digital Money Is Being Readied For Production*, *Forbes*. Available at: https://www.forbes.com/sites/vipinbharathan/2021/01/30/dxcd-the-eastern-caribbean-central-bank-money-is-being-readied-for-production/ (Accessed: 17 May 2021).

Borio, C (2019). On money, debt, trust and central banking. BIS Working Paper 763. https://www.bis.org/publ/work763.pdf?fbclid=IwAR3RAKoRMWbS6roMxel3UOMLMmzOuKDl12oV_WxC_y3C94D8CnhGEMxVX-Y

Birch, D. G. W. (2018) 'Who will make money? Tokens and the "5Cs" of future currency', *Journal of Payments Strategy & Systems*, 12(2), pp. 111–121.

BIS (2021) 'Multiple CBDC (mCBDC) Bridge'. Available at: https://www.bis.org/about/bisih/topics/cbdc/mcbdc_bridge.htm (Accessed: 16 May 2021).

Chainlink (2020) *What Is the Blockchain Oracle Problem?*, *Chainlink*. Available at: https://blog.chain.link/blockchain-oracle-problem-chainlink (Accessed: 17 May 2021).

Deutsche Börse (2021) *Deutsche Börse Group - DLT-based securities settlement in central bank money successfully tested*. Available at: https://www.deutsche-boerse.com/dbg-en/media/press-releases/-DLT-based-securities-settlement-in-central-bank-money-successfully-tested-2590444 (Accessed: 17 May 2021).

Dini, P. and Kioupkiolis, A. (2019) 'The alter-politics of complementary currencies: The case of Sardex', *Cogent Social Sciences*. Edited by R. Read, 5(1), p. 1646625. doi: 10.1080/23311886.2019.1646625.

EC (2019) *Joint statement by the Council and the Commission on 'stablecoins'*. Available at: https://www.consilium.europa.eu/el/press/press-releases/2019/12/05/joint-statement-by-the-council-and-the-commission-on-stablecoins/ (Accessed: 17 May 2021).

EC (2020) 'The Retail Payments Strategy'.

EC and TNS Opinion & Social. (2016) *Financial products and services: report.* LU: Publications Office. Available at: https://data.europa.eu/doi/10.2874/863808 (Accessed: 14 May 2021).

ECB (2019) *Goodbye EONIA, welcome €STR!*, *European Central Bank*. Available at: https://www.ecb.europa.eu/pub/economic-bulletin/focus/2019/html/ecb.ebbox201907_01~b4d59ec4ee.en.html (Accessed: 17 May 2021).

ECB (2020a) 'Payments in a digital world'. Available at: https://www.ecb.europa.eu/press/key/date/2020/html/ecb.sp200910~31e6ae9835.en.html (Accessed: 17 May 2021).

ECB (2020b) 'Report on a digital euro', p. 55.

ECB (2021) *As of 1 October 2019 EONIA is calculated with a reformed methodology tracking the euro short-term rate - Quick View - ECB Statistical Data Warehouse*. Available at:

https://sdw.ecb.europa.eu/quickview.do?SERIES_KEY=198.EON.D.EONIA_TO.RATE (Accessed: 17 May 2021).

ECCB (2021) *Bitt Partners with ECCB to Develop World's First Central Bank Digital Currency in a Currency Union | Eastern Caribbean Central Bank*. Available at: https://www.eccb-centralbank.org/news/view/bitt-partners-with-eccb-to-develop-worldas-first-central-bank-digital-currency-in-a-currency-union (Accessed: 17 May 2021).

Ellul, J. and Pace, G. J. (2021) 'Towards External Calls for Blockchain and Distributed Ledger Technology', arXiv:2105.10399 [cs]. Available at: http://arxiv.org/abs/2105.10399 (Accessed: 26 May 2021).

Federal Reserve (2020) *The Fed - What economic goals does the Federal Reserve seek to achieve through its monetary policy?*, *Board of Governors of the Federal Reserve System*. Available at: https://www.federalreserve.gov/faqs/what-economic-goals-does-federal-reserve-seek-to-achieve-through-monetary-policy.htm (Accessed: 17 May 2021).

Federal Reserve Bank of Boston (2020) *The Federal Reserve Bank of Boston announces collaboration with MIT to research digital currency*, *Federal Reserve Bank of Boston*. Available at: https://www.bostonfed.org/news-and-events/press-releases/2020/the-federal-reserve-bank-of-boston-announces-collaboration-with-mit-to-research-digital-currency.aspx (Accessed: 16 May 2021).

Fleischman, T., Dini, P. and Littera, G. (2020) 'Liquidity-Saving through Obligation-Clearing and Mutual Credit: An Effective Monetary Innovation for SMEs in Times of Crisis', *Journal of Risk and Financial Management*, 13(12), p. 295. doi: 10.3390/jrfm13120295.

Friedman, M. (1969) *The Optimum Quantity of Money and Other Essays*. Chicago: Adline Publishing Company.

Fries, M. and Paal, B. P. (eds) (2019) *Smart Contracts: Schlaue Verträge?* 1. Auflage. Tübingen: Mohr Siebeck, p. VIII, 142.

Gesell, S. (1906) 'The Natural Economic Order', p. 207.

Graeber, D. (2011) *Debt: The First 5000 Years.* Melville Books.

JPMorgan Chase & Co. (2020) *Letter to Shareholders from Jamie Dimon, Annual Report 2020*, *JPMorgan Chase & Co.* Available at: https://reports.jpmorganchase.com/investor-relations/2020/ar-ceo-letters.htm (Accessed: 17 May 2021).

Kharif, O. (2021) 'Crypto's Shadow Currency Surges Past Deposits of Most U.S. Banks', *Bloomberg.com*, 1 May. Available at: https://www.bloomberg.com/news/articles/2021-05-01/crypto-s-shadow-currency-surges-past-deposits-of-most-u-s-banks (Accessed: 17 May 2021).

Kiff, J. (2018) *LIBOR: World Reference Point*. Available at: https://www.imf.org/external/Pubs/FT/fandd/basics/54-london-interbank-offered-rate.htm (Accessed: 17 May 2021).

Kumhof, Michael and Noone, Clare, Central Bank Digital Currencies - Design Principles and Balance Sheet Implications (May 18, 2018). Bank of England Working Paper No. 725, Available at SSRN: https://ssrn.com/abstract=3180713 or http://dx.doi.org/10.2139/ssrn.3180713

Kuhn, D. (2020) *Bilateral Saudi, UAE Digital Currency Experiment Shows Benefits of Distributed Ledgers, Central Banks Say*, *CoinDesk*. Available at: https://www.coindesk.com/bilateral-saudi-uae-digital-currency-experiment-shows-benefits-of-distributed-ledgers-central-banks-say (Accessed: 17 May 2021).

Larsen, A. (2018) *A Primer on Blockchain Interoperability*, *Medium*. Available at: https://medium.com/blockchain-capital-blog/a-primer-on-blockchain-interoperability-e132bab805b (Accessed: 17 May 2021).

Ledger Insights (2021) *Bank of Japan starts one year digital yen CBDC trial*, *Ledger Insights - enterprise blockchain*. Available at: https://www.ledgerinsights.com/bank-of-japan-yen-cbdc-central-bank-digital-currency-trial/ (Accessed: 16 May 2021).

Littera, G. *et al.* (2019) 'From an idea to a scalable working model: Merging economic benefits with social values in Sardex', *IJCCR*, 11 September. Available at: https://ijccr.net/2019/09/11/from-an-idea-to-a-scalable-working-model-merging-economic-benefits-with-social-values-in-sardex/ (Accessed: 17 May 2021).

MAS proposes 'unbundling digital currency stack' (2021) *Central Banking*. Available at: https://www.centralbanking.com/node/7827156 (Accessed: 16 May 2021).

McLeay, M, Radia, A and Thomas, R (2014). Money Creation in the Modern Economy. Bank of England Quarterly Bulletin 2014 Q1, Available at SSRN: https://ssrn.com/abstract=2416234

Milne, A. (2018) *Argument by False Analogy: The Mistaken Classification of Bitcoin as Token Money*. SSRN Scholarly Paper ID 3290325. Rochester, NY: Social Science Research Network. doi: 10.2139/ssrn.3290325.

MIT (2020) *Building a Hypothetical CBDC*, *MIT Digital Currency Initiative*. Available at: https://dci.mit.edu/building-a-hypothetical-cbdc (Accessed: 16 May 2021).

Monetary Authority of Singapore (2020) *Project Ubin: Central Bank Digital Money using Distributed Ledger Technology*. Available at: https://www.mas.gov.sg/schemes-and-initiatives/project-ubin (Accessed: 16 May 2021).

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

Nick Szabo (1997) *View of Formalizing and Securing Relationships on Public Networks* | *First Monday*. Available at: https://firstmonday.org/article/view/548/469 (Accessed: 21 May 2021).

Oluwapelumi, A. (2021) *Tether Transaction Volume on Tron Blockchain Usurps That of Ethereum Blockchain*, *Coinspeaker*. Available at: https://www.coinspeaker.com/tether-transaction-volume-ethereum/ (Accessed: 17 May 2021).

Riksbank (2021) 'E-krona pilot phase 1', p. 21.

Simmons, R. *et al.* (2021) 'Crisis and the Role of Money in the Real and Financial Economies—An Innovative Approach to Monetary Stimulus', *Journal of Risk and Financial Management*, 14(3), p. 129. doi: 10.3390/jrfm14030129.

Statista (2021) *Facebook: daily active users worldwide*, *Statista*. Available at: https://www.statista.com/statistics/346167/facebook-global-dau/ (Accessed: 17 May 2021).

Tether (2021) 'Tether Releases Most Recent Independent Assurance Opinion Confirming Tether's Reserves Fully Backed | Tether', 29 April. Available at: https://tether.to/assurance-opinion-apr-21/ (Accessed: 17 May 2021).

Tompkins, M. and Olivares, A. (2016) 'Clearing and Settlement Systems from Around the World: A Qualitative Analysis', p. 46.

UNRISD (2014) *Social Drivers of Sustainable Development (Beyond 2015 Brief No. 4)* | *Publications* | *UNRISD*. Available at: https://www.unrisd.org/80256B3C005BCCF9/search/BC60903DE0BEA0B8C1257C78004C8415?OpenDocument (Accessed: 17 May 2021).

Visco, I. (2020) 'The role of TIPS for the future payments landscape'. Available at: https://www.bis.org/review/r201130c.pdf.

Walk, H. (2021) *Why There's No Such Thing as a 'Startup Within a Big Company'*, *Medium*. Available at: https://marker.medium.com/why-theres-no-such-thing-as-a-startup-within-a-big-company-c3003615f3bc (Accessed: 17 May 2021).

Wall Street Journal (2021) 'Transcript: Fed Chief Powell's Postmeeting Press Conference', *Wall Street Journal*, 28 April. Available at: https://www.wsj.com/articles/transcript-fed-chief-powells-postmeeting-press-conference-11619644895 (Accessed: 16 May 2021).

Werner, R A (2014). Can banks individually create money out of nothing? — The theories and the empirical evidence. International Review of Financial Analysis, Vol 36, pp 1-19. https://www.sciencedirect.com/science/article/pii/S1057521914001070

Wikipedia (2021a) 'Diem (digital currency)', *Wikipedia*. Available at: https://en.wikipedia.org/w/index.php?title=Diem_(digital_currency)&oldid=1022940118 (Accessed: 17 May 2021).

Wikipedia (2021b) 'The Innovator's Dilemma', *Wikipedia*. Available at: https://en.wikipedia.org/w/index.php?title=The_Innovator%27s_Dilemma&oldid=1023229110 (Accessed: 17 May 2021).

Wilson, T. (2020) 'Analysis: Central bankers comb for crypto clues as Bahamas launches "Sand Dollar"', *Reuters*, 21 December. Available at: https://www.reuters.com/article/us-cenbanks-digital-analysis-idUSKBN28S0KT (Accessed: 17 May 2021).

Wilson, T. (2021) *China's digital yuan will not topple the dollar, SEC official says*, *Reuters*. Available at: https://www.reuters.com/technology/chinas-digital-yuan-will-not-topple-dollar-sec-official-says-2021-04-29/ (Accessed: 16 May 2021).

World Economic Forum (2020a) *Bridging the Governance Gap: Interoperability for blockchain and legacy systems*, *World Economic Forum*. Available at: https://www.weforum.org/whitepapers/bridging-the-governance-gap-interoperability-for-blockchain-and-legacy-systems/ (Accessed: 17 May 2021).

World Economic Forum (2020b) *Inclusive Deployment of Blockchain for Supply Chains: Part 6 – A Framework for Blockchain Interoperability*, *World Economic Forum*. Available at: https://www.weforum.org/whitepapers/inclusive-deployment-of-blockchain-for-supply-chains-part-6-a-framework-for-blockchain-interoperability/ (Accessed: 17 May 2021).