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Central Bank Digital Currencies and Monetary Policy Effectiveness in the Euro Area

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Abstract

In consequence of the progressive digitalization and declining trend of cash-usage in payments, the majority of central banks is currently researching the topic of Central Bank Digital Currencies (CBDCs). Since 2020, the ECB is preparing a review into whether to issue a digital complement to physical cash and central bank deposits, the so-called digital euro. This study investigates its potential impact on the transmission of monetary policy. We first survey and interpret key properties of money and money-like assets in the current monetary framework, which motivates a discussion of the proposed forms of CBDCs and the digital euro. Against this background, we extend and close the arbitrage model of Meaning et al. (2018) to investigate the effect of CBDCs on the effectiveness of monetary policy transmission and the ability of the banking sector to fulfil regulatory liquidity requirements. We conclude that monetary policy would be effective following the introduction of interest-bearing CBDCs, potentially reinforcing the mechanism. Further, we confirm that an increase in non-pecuniary benefits of holding bank deposits in relation to CBDCs can mitigate the risk of a potential disintermediation of the banking sector.

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"*We should be prepared to issue a digital euro, should the need arise.*"
(Lagarde, 2020)

1 Introduction

Digitalization has changed customers' payment preferences and added an international layer to the payment landscape. The declining trend of central bank issued cash-usage in advanced economies was accelerated by the COVID-19 pandemic (Panetta, 2020). Since the turn of the century, non-cash payments have roughly doubled in size as a share of GDP (BIS, 2018). In 2019, only 48 percent of total transaction value in the euro area were made in cash (ECB, 2020). Customers increasingly use commercial bank money for electronic payments as well as private sector payment technologies (Coeuré, 2018). In addition, the private sector has invented "cryptocurrencies",[1] such as Bitcoin and other blockchain-based digital tokens, which further pave the way for a digitalization of payments and the monetary system.

Several challenges arise from these trends, which have induced central banks to research the issuance of a complementary digital liability. First, Europeans are currently using mainly American payment platforms with no equivalent European competitor available. This implies a high European dependence on foreign companies and the US dollar (Mayer, 2019). Second, these trends generally involve an increasing dependence on profit-maximizing private firms, which operate personal transaction data for the public good of trusted money. It is questionable whether this can be socially optimal.

To improve the usability of central bank money and to avoid associated risks of private sector solutions (for further motivations, see, e.g., Bank of England, 2020), central banks are researching whether to issue a new electronic form of money. Currently, about 86 percent of central banks are researching the topic of Central Bank Digital Currencies (CBDCs) (Boar and Wehrli, 2021). Among those, national initiatives of the Bank of Canada, the Bank of England, the Bank for International Settlements, the IMF, the People's Bank of China, and the Sveriges Riksbank, but also international collaborations explore the desirability of issuing an electronic form of public money (Daavoodalhosseini et al., 2020; Barrdear and Kumhof, 2016; BIS, 2020; Armelius et al., 2018; Group of 30, 2020). In the euro area, the ECB is preparing a review into whether to issue its own digital complement to physical cash and central bank deposits, the so-called digital euro (ECB, 2020).

The new and ongoing discussion involves a rapidly growing literature on CBDCs and their possible consequences, predominantly conducted by central banks. Although, rapidly growing, associated literature remains in its infancy.

[1] A currency is a constitution and order of the monetary system of a state (Thiele and Diehl, 2020). As such, the term "currency" is misleading in the context of digital money-like assets, such as Bitcoin, because it is not backed by the government, but a private initiative. Further, some monetary economists claim universal access as a distinctive feature of any currency (cf. Bjerg, 2017; Fung and Halaburda, 2016).

Conceptual Research A first strand of the literature provides conceptual research on the functions of money and CBDCs (see, e.g., Bordo and Levin, 2017) and compares the characteristics of bank deposits, banknotes, and reserves with potential CBDC design features. For instance, the "money flower" Venn diagram of Bech and Garratt (2017) offers a taxonomy of money and defines CBDCs as central bank issued, electronic money, which is accessible to all. Bjerg (2017) studies three scenarios, where CBDCs are introduced alongside with cash and bank deposits or as a substitute for either one. Further design choices are analyzed, e.g., by Agur et al. (2019), Allen et al. (2020), BIS (2020), Engert and Fung (2017), and Kumhof and Noone (2018).

Yet, most of the literature on CBDC is purely descriptive with f

ormal theoretical models including CBDCs essentially underrepresented. We briefly focus on models including a banking sector before turning to the effect of CBDC on financial stability and monetary policy.

The seminal work of Barrdear and Kumhof (2016) introduces an interest-bearing CBDC in a DSGE model calibrated to the United States. The authors assume an initial CBDC issuance of 30 percent of GDP against government debt. Their results suggest a reduction in real lending and deposit rates - although by less than the decline in the policy rate – leading to an overall GDP increase of 2.94 percent. Furthermore, the central bank benefits from having control over an additional monetary policy tool in form of the CBDC rate or quantity.

Formal models of the impact of CBDC on deposit-taking institutions remain inconclusive. On the one hand, the introduction of interest-bearing CBDCs can reduce bank deposits and lending (see, e.g., Keister and Sanches, 2019; Williamson, 2019). On the other hand, Andolfatto (2018) develops an overlapping generations framework with a monopolistic banking sector to show that interest-bearing CBDCs promote efficiency by reducing the bank's monopoly profit. Andolfatto (2018) argues that bank deposits increase if CBDCs force banks to increase deposit rates. Chiu et al. (2019) confirm these results with the help of a New Monetarist model with imperfect competition, which shows that CBDCs can increase bank lending by approximately 7 percent and output by about 1 percent when calibrated to the US economy.

Financial Stability Regarding financial stability issues, the majority of the (mainly descriptive) literature argues that CBDC can have a destabilizing effect on the financial system, mainly stemming from the competition between bank deposits and CBDCs (see, e.g., Fernandez-Villaverde et al., 2020, Carletti et al., 2020). The introduction of CBDCs can result in a potential loss of deposits, threatening bank funding and, thus, bank lending in both, normal and crises times. According to Juks (2018) even the introduction of non-interest bearing CBDCs can potentially lead to increased deposit outflows in distressed times, on condition that CBDCs would be more attractive than cash holdings. This, in turn, can decrease bank lending (Juks, 2018) and worsen the compliance with liquidity requirements as imposed by Basel III (BCBS, 2013).

Further, the literature is ambiguous on whether these stability risks can be mitigated. According to Kumhof and Noone (2018), deposits are not replaceable by CBDCs. By contrast, Juks (2018) argues in favor of a substitution of lost deposits with wholesale funding by issuing new bonds. Brunnermeier and Niepelt's (2019) model claims a credit crunch can be mitigated if the central bank provides sufficient refinancing opportunities for banks' deposit loss (see also Mancini-Griffoli et al., 2018; Meaning et al., 2018; Pfister, 2017). Besides a quantitative replacement, Andolfatto (2018) and Mancini-Griffoli et al. (2018) suggest a bank to prevent deposit loss by increasing the deposit rate.

Monetary Policy The impact of CBDCs on the effectiveness of monetary policy is a more intensely researched topic. It refers to interest-bearing CBDCs only, otherwise the policy rate of the central bank continues to be the monetary policy instrument and monetary policy can largely remain as it is today (Nessén et al., 2018). Non-interest-bearing CBDCs, thus, are unlikely to strengthen the transmission mechanism (Armelius et al., 2018). Interest-bearing CBDCs can potentially solve the problem of cash hoarding to avoid negative interest rates, and thus, lower the Effective Lower Bound (Bordo and Levin, 2017; Meaning et al., 2018). This, however, would require a restriction on cash holdings, which is questionable (Davoodalhosseini et al., 2020). Further, it is argued that interest-bearing CBDCs offer a new monetary policy tool, tend to enhance transparency (Bordo and Levin, 2017) and allow a more direct implementation and transmission mechanism (BIS, 2018; Davoodalhoessini et al., 2020). However, these suggestions are, again, only of descriptive nature. Meaning et al. (2018) offer a formalization and use an arbitrage model to suggest an improved pass-through of policy rate changes when CBDC are implemented.

Contribution The aim of this study is to provide two-fold insights regarding the ECB's digital euro initiative. Our first contribution is to survey and interpret the framework in which CBDCs would be introduced. This facilitates drawing a clear comparison between current asset characteristics and the key properties of a future digital euro, referring to both, its store of value function as well as a medium of exchange. Further, it motivates the general introduction of CBDC.

Against this background, we refine the balance sheet analysis of Meaning et al. (2018). We extend and close their arbitrage model to study the effects of the introduction of interest-bearing retail CBDCs on (i) the transmission of conventional monetary policy and (ii) macroprudential policy in the absence of central bank reserves by focusing on the effects on deposit, lending, and bond rates. While Meaning et al. (2018) propose that CBDCs strengthen the monetary policy transmission mechanism, our main results rather resemble those in the current monetary system. Further, we study the effect of the introduction of CBDCs on deposit and lending rates, potentially destabilizing the financial system as analyzed with the help of a liquidity measure resembling to the Liquidity Coverage Ratio.

The article is organized as follows. Section 2 recaptures the key properties of money in the current monetary system, money-like assets of the private sector, and CBDCs as well as the digital euro. Section 3 introduces the model. We present our main results regarding the transmission of monetary policy and financial stability in Section 4. Section 5 discusses resulting policy implications, and, finally, we draw a conclusion in Section 6.

2 Key Properties of Money and Money-Like Assets

The definition of money generally refers to three main functions as medium of exchange, unit of account, and store of value. In the following, the non-pecuniary benefits of a medium of exchange and the pecuniary benefits of the store of value function are discussed as related to the current monetary system and private sector money-like assets. Finally, the functions of CBDCs and the digital euro proposal are discussed to allow for a comparison between the different types of money.

2.1 Money in the Current Monetary System

The current monetary system of the Eurosystem is two-tiered. Due to the different nature of money, a distinction can be made between, on the one hand, money issued by the central bank, and on the other hand, commercial bank money. Both forms of money can be exchanged at par, although characterized by different (non-)pecuniary returns and benefits.

Tier 1: Central Bank Issued Money The monetary authority has monopoly power over the creation of central bank money, which is usually associated with the lowest level of default risk, highest credibility, and trust in its stability. The ECB supplies central bank money in the form of electronic reserves, which are only available to the banking sector, and in the form of physical banknotes, which are universally accessible, but distributed via financial institutions (coins are issued by national authorities). Its supply creates a positive seigniorage as long as the interest received on granted loans and purchased assets exceeds the interest payable on liabilities (Mayer, 2019).

In the Eurosystem, the main refinancing operation (MRO) is the most important standard instrument for reserve supply. This credit operation with a one-week maturity currently operates under full allotment. Hence, the demand for reserves is currently always satisfied, given suitable collateral. Banks' reserve demand arises, e.g., from the minimum reserve requirement as well as autonomous factors, such as banknotes in circulation.

Traditionally, minimum reserve holdings yield a low, close to zero pecuniary return, while excess reserve holdings are not remunerated. Banks have additional non-pecuniary benefits of holding reserves in the form of a regulatory advantage as they are considered as high-quality liquid assets (HQLA) in the

Basel liquidity framework (BCBS, 2013). Moreover, reserves can be transferred at high speed. By contrast, non-pecuniary costs of reserves refer to a central bank account-based record and a geographical range restricted to the domestic country.

Banknotes are universally accessible to banks as well as non-banks, although the non-bank access is intermediated by the banking sector. As legal tender, banknotes are protected by EU law (Article 128(1) TFEU) and in this way safeguard fundamental rights (Mersch, 2018). Since banknotes are non-interest bearing, the non-bank private sector demand for physical central bank money is assumed to be mainly driven by non-pecuniary returns of transaction purposes, such as a high level of privacy and data protection to its user. The exchange of banknotes in person implies, on the one hand, an immediate and final settlement of transactions, but also a restriction to local transfers, not to mention cross-border payments, on the other. Additional downsides of physical banknote holdings are, for instance, storage costs, the risk of theft and anonymity, which also opens the door to abuses like money-laundering. In contrast to the non-bank private sector, the banking sector is subject to negative interest rates on reserve holdings as imposed by the Eurosystem since 2014. This has induced banks to increasingly hold banknotes (Lalouette and Esselink, 2018), which offer the additional benefit of a reduction in regulatory costs as they are considered as HQLA. The usage of banknotes by the non-bank private sector, however, is subject to a declining trend. If banknotes were no longer used, the public would be wholly dependent on commercial bank money (Coeuré, 2018) as described in the following subsection.

Tier 2: Commercial Bank Issued Money A universally accessible kind of fiat money is electronic deposits held at a commercial bank account. According to the credit creation theory of McLeay et al. (2014) commercial banks create money by credit extension. In addition to a minimum reserve requirement, a capital requirement restricts commercial bank money supply (BCBS, 2011). Credit creation yields a net interest margin between the return on loan provision and the cost of the deposit rate.[2]

The non-bank private sector demands commercial bank money for real capital investment at the cost of the loan rate. In return, they receive deposits, which pay the lower deposit rate. In addition, bank deposits offer non-pecuniary costs and benefits as medium of exchange, allowing private agents to use the fast exchange of means of payment by electronic bank transfer. However, compared with banknotes, transactions are less anonymous as every transfer creates an account-based record. Due to its domestic currency denomination, it is restricted to the local country, and banks may charge additional costs, such as a bank account fees or for the usage of ATMs. Further, the non-bank private sector faces the risk of bank default when holding bank deposits.

[2] Deposit associated service provisions are increasingly overtaken by private platforms via which commercial bank money can be transferred (cf. Paypal as a prominent example). Importantly, Europeans currently use predominantly American payment platforms, which results in a high European dependence on foreign companies and the US dollar (Mayer, 2019).

In summary, the non-bank private sector can hold monetary claims on the central bank in the form of banknotes and claims on commercial banks in the form of electronic deposits. If cash-usage continues to decline, ultimately, the public would be entirely dependent on commercial bank issued money (Coeuré, 2018). The banking sector can hold reserves in addition to banknotes. Furthermore, it can create its own money by credit provision, where an excessive level of debt and fast growth by credit creation can have adverse effects on macroeconomic stability (see, e.g., Bernanke, 2010; Gourinchas and Obstfeld, 2012).

2.2 Private Sector Solutions

The emerging mistrust in commercial bank money during the Global Financial Crisis (GFC) resulted in bank runs, when depositors suddenly demanded central bank instead of commercial bank money. Today, apparently even trust in the central bank has been eroded with 45 percent of area residents expressing mistrust of the ECB in 2020 (European Commission, 2020). Therefore, private initiatives launching crypto assets are increasingly gaining attention and market value.

At the peak of the GFC, Nakamato (2008) established a counter project to commercial bank money, the seminal crypto asset Bitcoin. The electronic payment system claims to operate without the precondition of trust in any institution, either intermediary or governmental. Today, the private sector accounts for more than 2000 different kinds of crypto assets (Bullmann et al., 2019), which have reached a total global market value of approximately 878 billion US dollar (CoinMarketCap, 2020). In the following, we review the key properties of Bitcoin as the most prominent and dominant example and briefly draw its distinction to "stablecoins".

Bitcoin System The anonymous inventor of Bitcoins justified the introduction of this kind of electronic network on the grounds of a lack of trust in central bank and commercial bank money (Nakamoto, 2008). According to Nakamoto (2008) it is "*based on cryptographic proof instead of trust.*" However, Bitcoins do not have an intrinsic value and thus, rely on users' trust in its convertibility and stability regarding its function as a store of value. The missing intrinsic value incurs a high risk of default as well as high volatility of the crypto asset's real value (Chiu and Koeppl, 2019) with Bitcoin's purchasing power determined by demand and supply of the Bitcoin itself. It is not backed by other assets (Mayer, 2019) nor by anyone.[3] Ultimately, Bitcoin is rather regarded as a speculative asset than money (see, e.g., ECB, 2020; Yermack, 2013).

By contrast to commercial bank money, the global supply of Bitcoins is quantitatively restricted to 21 million. Given an increase in demand, an investment in Bitcoins yields a pecuniary return in the form of an increase in market

[3] According to the ECB (2019, p.3), a crypto asset is defined as *"a new type of asset recorded in digital form and enabled by the use of cryptography that does not represent a financial claim on, or a liability of, any identifiable entity."*

value. Bitcoin's market value is subject to high volatility as analyzed, e.g., by Schilling and Uhlig (2019).

The decentralized system is based on the distributed ledger technology (DLT), i.e., Blockchain in case of Bitcoins, which records all transactions. In the absence of a central authority, so-called nodes verify every initiated transaction (avoid double-spending, solve a hash-puzzle by extending the block in competition with others), which takes on average ten minutes (Halaburda et al., 2020). On the one hand, this technology safeguards a high system security by extending blocks on a random basis (Siegel and Stulle, 2018). On the other, this process reduces the speed of settlement when compared with cash transactions. As opposed to banknotes, crypto assets cannot achieve immediate and final settlement due to the needs of double-spending avoidance and block extension (Chiu and Koeppl, 2019). In addition, the system's processing capacity currently falls far behind credit card systems (Siegel and Stulle, 2018). According to Chiu and Koeppl (2019), these costs lead to an approximately 500 times higher welfare loss of a Bitcoin economy in its 2015 design than a monetary economy with 2 percent inflation. In the long run, however, these costs are expected to be reduced significantly (Chiu and Koeppl, 2019).

Although designed as a payment system, there is an ongoing discussion whether Bitcoins are rather demanded as a medium of exchange or speculative investment asset (see, e.g., Biais et al., 2020; Selgin, 2015). Despite of a current tendency to speculative asset rather than money (Baur et al., 2018; ECB, 2020; Thiele and Diehl, 2017; Yermack, 2013), we briefly introduce the non-pecuniary costs and benefits of holding Bitcoins.

First, the privacy of transactions in Bitcoins is subject to a controversial debate. Intended to protect payment data from banks and enable private payments, Nakamoto (2008) claims that the system reveals every transaction to the public but keeps the identities of the parties involved private. By contrast, Brito and Castillo (2013) classify the system as "pseudo-anonymous" due to the availability of all transactions in the public ledger for any interested party. The Blockchain technology, however, is not subject to banking secrecy rules and IP-addresses at least allow for tracing back to the payment initiator (Mayer, 2019). Thus, concerns have been raised especially with regard to money laundering and consumer protection (ECB, 2019).

Since Bitcoins are not bound to national borders nor authorities, they allow for cross-border transactions at similar speed as national transfers. This is a major advantage of Bitcoins when compared with cross-border transfers of commercial bank deposits. However, generally, the utility of every means of exchange depends on its number of users. The banking sector has no incentive to hold Bitcoins for regulatory benefits because it is currently not considered as HQLA.

"Seigniorage" from issuing new Bitcoins is distributed to "miners" who receive a reward for updating the Blockchain (in addition to transaction fees). Currently, the reward is 6.25 Bitcoins, which halves quadrennial and is expected to be completed around 2040 (Baur et al., 2018). The established mechanism hinders inflationary processes, but it is expected that increasing transaction fees will substitute for the declining mining profits (Nakamoto, 2008).

Although intended to avoid additional costs of small payments charged by banks (Nakamoto, 2008), transaction fees charged by the Bitcoin network have been very volatile and occasionally even prohibitively high for small payments (Siegel and Stulle, 2018).

In consequence, if only Bitcoins were to be used for transactions, the banking sector would have to change its business model and shift from credit creation to intermediation between savers and borrowers (Mayer, 2019). Furthermore, in the absence of a responsible issuer, a Bitcoin economy would make the central bank redundant, and monetary policy as well as regulatory oversight challenging. However, Bitcoin has not yet established itself as a global means of payment due to its scalability, volatility, and regulatory uncertainty (Groß et al., 2020). Due to its high price volatility, a complete substitution of (central) bank money by Bitcoins is rather unlikely, which implies a rather limited impact on central banking at this stage.

Stablecoins To address the issue of high price volatility, private initiatives have developed another kind of crypto assets, called stablecoins (Bullmann et al., 2019). In contrast to Bitcoins, their market value is backed by assets, such as gold, fiat currencies, traditional asset classes like government bonds or other crypto assets. As a prominent example, Tether's value is fixed at par with the US dollar. The stabilizing interventions can be executed by institutions, users, or automated algorithms (Bullmann et al., 2019), which e.g., issue new coins given an excessive market value due to increased demand. This implies a centralization and a loss of control regarding the coin supply as compared with Bitcoins. Contrary to crypto assets, stablecoins can entail a claim on an identifiable entity (Bindseil, 2020). Their properties, however, depend on the type of claim they represent, which can resemble commercial bank money, investment funds, or crypto assets (Bullmann et al., 2019).

In 2019, the Libra Association (2019), led by Facebook, announced a launch of Diem (formerly known as Libra) in 2021. Adachi et al. (2020) estimate Libra/Diem's potential market value between 150 and 3000 billion euros, which has caused financial stability concerns.

Contrary to Bitcoins, its supply adjusts fully elastically to demand (Groß et al., 2020). Libra/Diem holdings are generally not interest-bearing, the system only promises to repay at the then given future Libra/Diem value. Usually, stablecoins are backed by one single currency, but the Libra Association (2019) initially planned to back it by a multi-currency basket and government bonds. The adapted concept of Diem now foresees (a) single-currency backed coins, such as LibraEUR, and (b) a multi-currency coin in the form of a basket of the single-currency coins. The Libra Association (2019) specifically mentions that central bank digital currencies could be included in the future.

Both single- and multi-currency coins will be completely backed by a "Libra reserve" of 20 percent cash or cash equivalents and 80 percent short-term government securities denominated in the respective currency, which should maintain

Libra/Diem's store of value function. By completely backing each coin with stable and liquid assets, the coin gains intrinsic value. In addition, Libra/Diem would extend the current two-tier system to a three-tier system (Groß et al., 2020).

The Libra Association has also applied for a license of its payment system. Under a fixed LibraEUR-Euro exchange rate system, the Libra Association would offer a global payment system with Libra/Diem as close substitute to commerical bank money (Groß et al., 2020) and become a competitor for payment services of commercial banks.

Like Bitcoin, Libra/Diem aims to serve as global means of exchange (Libra Association, 2019) and offers privacy with transfers under pseudonyms (Mayer, 2019). The non-pecuniary benefit from holding Diem as means of exchange includes a significantly higher rate of transactions per second than Bitcoin, which, however, still falls short in comparison with the credit card networks (Mayer, 2019). Contrary to Bitcoins, transfers of Libra/Diem are planned to be free of charge as long as backing fiat-currencies pay sufficient interest to cover the costs of the Libra Association (Mayer, 2019).

The "seigniorage" results from Libra/Diem purchases with existing currencies. For new Libra/Diem to be created, there must be an equivalent purchase of Libra/Diem for fiat and transfer of that fiat to the reserve. However, users do not receive a return from the reserve, which can be invested in low-risk assets, such as bank deposits and short-term government bonds. Resulting returns will go entirely to the Libra Association, which claims to use it to cover the system's costs.

2.3 Central Bank Digital Currencies

Motivated by the trend of a decline in cash usage and arising challenges of global private digital money initiatives, central banks have intensified the investigation of a future issuance of CBDCs. The creation of a new, risk-free kind of central bank liability represents a digital complement to physical banknotes and central bank deposits (ECB, 2020). CBDCs would probably be freely convertible and exchanged at par with the central bank's other liabilities (He et al., 2017). In the following, we will refer to the definition of Meaning et al. (2018, p. 2) according to which "*Central bank digital currency is an electronic, fiat liability of a central bank that can be used to settle payments or as a store of value.*"

CBDCs can be classified into wholesale and retail CBDC by type of access. While the access to wholesale CBDCs is limited to financial institutions, retail or "general purpose" CBDCs are accessible to all. Hence, wholesale CBDCs are closer to today's central bank reserve and settlement accounts used in interbank markets, which would not substantially change the current two-tier monetary system. This can also explain why research on wholesale CBDCs is underrepresented (see, e.g., the studies of Boar et al. (2020) or Pfister (2020)). By contrast, retail CBDCs rather represent a digital complement to riskless cash holdings, which would lead to a fundamental change in the current monetary system.

Further, token-based and account-based CBDCs are distinguished, which differ by verification requirements (Kahn and Roberds, 2009). Like the exchange of physical banknotes, token-based CBDCs can be traded on a peer-to-peer basis, i.e., without intermediary. This offers a high level of privacy in transactions and is proposed, e.g., for the Fedcoin (Koning, 2014). Token-based CBDCs require a verification of the object used to pay. By contrast, account-based CBDCs require the verification of the identity of the payee with a subsequent record of every change in deposits on the associated bank account.

The provision infrastructure can be based on conventional centralized technology or on DLT. As named above, DLT often aims to replace trust in financial intermediaries with trust in technology. By contrast to the permissionless Bitcoin system, central banks researching DLT rather focus on variants in which operators have to permit access to the system (Auer et al., 2020).

With issuance by the central bank, the supply of CBDCs is centralized. However, CBDC users can hold a direct or an indirect legal claim on the central bank. In the latter case, CBDCs were a direct claim on an intermediary. The operational role of the central bank is to be determined in each scenario. CBDCs and all related services can be provided exclusively by the central bank or (partly) transferred to an intermediary, such as the banking sector or a third party.

In addition, it has to be considered whether CBDCs should yield a pecuniary return. Like commercial bank deposits, CBDCs can be interest-bearing, which could be used as a new monetary policy instrument to affect inflation and output. For retail CBDCs, the interest rate could move with the policy rate of the central bank and apply more directly to the non-bank private sector, thereby improving the transmission of monetary policy to the non-bank private sector (BIS, 2018), but potentially also weaken the transmission to bank rates. Furthermore, interest-bearing CBDCs can potentially lower the ELB (Bordo and Levin, 2017). Alternatively, non-interest bearing CBDCs would be a closer substitute for banknotes as means of payment, which would have negligible effects on monetary policy (Broadbent, 2016).

The functional design requires CBDCs to offer a clear benefit to users in order to create CBDC demand. The use of CBDCs as means of exchange reduces transaction costs and enhances the efficiency of the payment system. Settlement time can be significantly reduced (Bank of England, 2020), especially regarding cross-border payments. A DLT-based CBDC can reduce the complexity of payment systems by reducing the number of intermediaries involved (Groß et al., 2020), thereby also reducing transaction fees. Further, costs of small value payments can be reduced, and payment security increased (He et al., 2017). The utility offered by CBDCs for cross-border payments depends on future arrangements with other central banks. Further, the central bank has to decide whether to make CBDCs accessible to non-residents, too, which is, e.g., naturally the case for token-based CBDCs. Privacy of transactions in CBDCs depends on the technology used, with higher anonymity offered by token-based CBDCs. Although the BIS (2020) names the low costs of any CBDC as a key priority, additional costs will depend on the specific design choices of each central bank.

For instance, banks can charge account fees given access to CBDCs would be intermediated via the banking system.

Digital Euro In order to improve the payment system, safeguard the efficiency of monetary policy and to secure the trust in the euro, the ECB (2020, p. 6) considers creating a new, risk-free "*liability of the Eurosystem recorded in digital form as a complement to cash and central bank deposits.*" In its seminal report, the ECB (2020) points out the main objectives and broad design principles of a future CBDC, which it names the digital euro.

The ECB (2020) generally refers to retail CBDCs as universally accessible central bank money, which will also be the focus of our study. The digital euro will be convertible at par with banknotes, reserves, and commercial bank money (ECB, 2020). Moreover, the ECB (2020) does not exclude any possibility of the technological design and hence, refers to a token- as well as an account-based digital euro, which could possibly co-exist. The following section briefly summarizes the two concepts of the digital euro as presented in the ECB's (2020) report.

First, the "bearer digital euro" refers to a token-based CBDC, which can be used for offline peer-to-peer transactions and settlement. A major advantage for users of the bearer digital euro is its high degree of privacy and data protection, which can be compared to transactions in cash. This anonymity of transactions, however, can also bear financial risks including legal challenges. The ECB (2020) plans to set standards and provide the technological infrastructure (DLT or local storage) to intermediaries, which take on associated services, such as distribution and loading of, e.g., prepaid cards. Intermediaries can charge service fees, although the bearer digital euro should be supplied at low cost. The bearer digital euro would yield a fixed, non-negative (but probably zero) pecuniary return . In addition, its supply would probably be limited per user. By contrast, a hybrid bearer digital euro could be introduced in an account-based infrastructure, where intermediaries could provide retail payment services and settlement. This concept could also use the current wholesale payment infrastructure.

The second, "account-based digital euro" approach foresees user access via a Eurosystem account, either directly or indirectly via intermediaries. In the former case, e.g., private keys could be stored with end-users, which imposes technical and organizational challenges (ECB, 2020). CBDC users would initiate payments, which were settled by the Eurosystem itself or by intermediaries on behalf of end-users. Payments could be settled by conventional, centralized technology, such as the TARGET Instant Payment Settlement (TIPS) system, which allows fast transactions. While the speed of transactions is a major advantage of an account-based digital euro, compared with the bearer approach, this approach would allow for less privacy, but similar data protection to commercial bank deposits. Regarding the pecuniary return of this approach, a variable interest rate is suggested, which can serve as an additional monetary policy instrument that can directly affect consumption and investment of the non-bank private sector. Further, the remuneration can be two-tiered with less interest on large or foreign CBDC holdings.

Based on the ECB's (2021) survey, according to which 41 percent of participants prefer privacy as the key non-pecuniary benefit regarding a digital euro, followed by security (17 percent) and pan-European reach (10 percent), a bearer digital euro apparently offers higher non-pecuniary benefits in the form of higher privacy than an account-based form. Assuming the demand for CBDCs to be determined by pecuniary and non-pecuniary benefits, a bearer digital euro can potentially allow the ECB to set a lower interest rate than on an account-based form (see Appendix A.1).

Regarding monetary policy and financial stability implications, the ECB (2020) hypothesizes a potential competition between bank deposits and an interest-bearing digital euro, increasing bank funding costs, and, thus, reducing credit supply. In response, the ECB (2020) suggests that banks either provide additional services or replace lost deposits by other funding sources, such as (a) central bank borrowing, which needs adequate collateral and thus, might affect market interest rates for those assets, or (b) capital market-based funding. In addition, the ECB (2020) takes increased risk-taking of banks into consideration, resulting from an incentive to compensate for their increased funding costs. Moreover, the reduction of bank payment data and customer information can deteriorate banks' risk assessment capacity, which can affect bank risk on a more general level.

The results are summarized in Figure 1, which relates key properties of the current types of money to private sector solutions, CBDCs in general and the planned digital euro as previously discussed.

The impact of the introduction of CBDCs on central bank seigniorage depends on the characteristics of the implemented approach. Given that CBDC holdings are interest-bearing, a positive interest rate can reduce seigniorage if the new exceeds the current interest payable on banknotes and (excess) reserve holdings. Table 1 exemplarily depicts a simplified balance sheet of the central bank. While the central bank receives interest payments on asset holdings and credit operations, it usually pays an interest rate on reserve holdings on the liability side, while banknotes are non-interest bearing. Depending on the design choice of the central bank, CBDCs are interest-bearing or not.

Table 1: Simplified Balance Sheet of the Central Bank

Central Bank

Assets	Liabilities
Credit operations	Banknotes
Assets	Reserves
	(CBDCs)

	Current types of money			Private sector solutions		CBDCs		
	Central bank money		Commercial bank money			General	Digital euro	
	Reserves	Bank-notes	Deposits	Bitcoins	Libra/ Diem		Bearer digital euro	Account-based digital euro
Liability of the central bank	✓	✓	X	X	X	✓	✓	✓
Electronic form	✓	X	✓	✓	✓	✓	✓	✓
Universal access	X	✓	✓	✓	✓	(*)	✓	✓
Interest bearing	(✓) (excess reserves)	X	(✓)	X	X	(*)	X fixed (probably 0)	✓ variable (linked to policy rate, evtl. tiered)
Convertibility (trades at par with other CB liabilities)	✓	✓	✓	X	?	(*)	✓	✓
Limited supply	X	X	X	✓	X	(*)	(✓)	X
DLT	X	X	X	✓	✓	(*)	(✓)	X
Front-end infrastructure (token- or account-based)	CB-**A**	**T**	B-**A**	**T**	**A**	(*)	**T**	CB-/B-**A**

Own representation based on Bech and Garratt (2017), BIS (2018), Meaning et al. (2018), ECB (2020)

✓ = existing or likely feature, (✓) = possible feature, X = not typical or possible feature , (*) = depends on central bank's design choice
CB= central bank; B= bank; C= centralised, D= decentralised; T= token-based, A= account-based

Figure 1: Characteristics of CBDC and other Money-Like Assets

3 The Model

In the spirit of Meaning et al. (2018), we consider a stylized model of a neoclassical economy including a monopolistic banking sector and a non-bank private sector to study the effectiveness of monetary policy transmission. Although having concretized, for instance, non-pecuniary benefits and costs of different kinds of assets, the model is still rather based on sensible assumptions than strict microfoundations to motivate risk and interest rate premia. In accordance with Meaning et al. (2018), the presented model abstracts from the central bank's balance sheet. Instead, the pass-through of changes in the CBDC rate to non-CBDC rates in the economy, such as deposit, loan, and bond rates, is analyzed in further detail.

In the following, we will study the effect of the introduction of retail CBDCs, as suggested by the ECB (2020). Moreover, we will refer to interest-bearing CBDCs, having the largest change when compared to the current framework. Furthermore, the following sections refer to account-based CBDCs, which are a direct claim of the non-bank private sector on the central bank.

In line with Meaning et al. (2018), we refer to CBDCs as the only central bank liability (see, e.g., Kumhof and Noone (2018) or Barrdear and Kumhof (2016) for analyses including CBDCs and reserves). First, we abstract from reserve holdings and CBDCs coexisting as distinct assets, since they offer similar non-pecuniary benefits to the banking sector as well as their supposedly free convertibility at par (ECB, 2020; He et al., 2017). The results of a model including both, namely CBDCs and reserves, would yield results close to the given scenario without reserves (see also Meaning et al., 2018). Second, we abstract from banknotes for reasons of simplification. However, it is important to note that we do not assume the complete removal of physical banknotes with the introduction of CBDCs. The striking difference after CBDC introduction is that the non-bank private sector can now hold electronic central bank money. We assume the non-bank private sector to partially substitute their financial asset holdings into CBDCs. The effect on the size and composition of their asset portfolio depends on the magnitude of the associated substitution effect per asset (see Bindseil (2020) for a flow of funds balance sheet analysis).

We subsequently consider the banking and the non-bank private sector in a closed economy and describe the arbitrage conditions implied by the composition of respective balance sheets as depicted in Table 2 below.

Table 2: Balance Sheets of the Banking and Non-Bank Private Sector

Banking Sector				**Non-Bank Private Sector**			
Assets		Liabilities		Assets		Liabilities	
Loans	L	Deposits	D	Deposits	D	Loans	L
Bonds	B			CBDCs	C		
CBDCs	C	Net wealth	w_b	Bonds	B		
				Real assets	K	Net wealth	w_p

Each of the following subsections differs slightly from the model of Meaning et al. (2018). Asset properties differ mainly in endogenous non-pecuniary benefits to the banking sector and concretized transactional benefits of holding CBDCs or bank deposits to the non-bank private sector. This approach allows us to specifically determine asset demand functions instead of arbitrage conditions between interest rates only as suggested by Meaning et al. (2018).

3.1 The Banking Sector

We begin with a description of the balance sheet composition of the banking sector, which leads us to the associated portfolio optimization problem. To keep the analysis as simple as possible, we consider a representative monopolistic bank, providing loans and accepting deposits.

Consistent with the balance sheet in Table 2, the asset side of the banking sector's balance sheet records loans, government bonds and CBDCs, which are financed by deposits of the non-bank private sector. For simplification, we assume each of these assets to be one period in term but able to be characterized by different risk-return combinations.

According to the credit creation theory of McLeay et al. (2014), every loan provision (L) to the non-bank private sector is assumed to simultaneously create a deposit in the banking sector's balance sheet. The banking sector receives the lending rate (R^L) on every loan provision. Borrowers are assumed to default with a probability of $0 < \mu < 1$. Furthermore, we assume all loans to be subject to managing and managing costs of

$$M(L) = \frac{1}{\tau} L^{\tau} \tag{1}$$

with $\tau > 1$, satisfying $\frac{d(M(L))}{dL} > 0$ and $\frac{d^2(M(L))}{(dL)^2} \geqslant 0$ to reduce moral hazard (Diamond, 1991). See Goodfriend and McCallum (2007) for a more detailed model including monitoring and collateral costs. Loan provision, however, does not provide transactional and liquidity services to the banking sector.

Besides loans, the banking sector holds CBDCs (C). We assume this claim on the central bank to be risk-free, but interest-bearing, where each unit of CBDC provides a pecuniary benefit denoted by R^C. In addition, CBDCs are assumed to provide additional services as means of exchange. The non-pecuniary benefit to banks is given by ϕ^B, which, e.g., lowers transaction costs and reduce settlement time and transaction fees.

The third asset, government bonds (B) is assumed to carry a higher risk-return combination than CBDCs. Government bonds are interest-bearing (R^B) but they add to portfolio risk, too, as denoted by $\sigma_B(B)$, which is assumed to be given by

$$\sigma_B(B) = \delta \frac{1}{\sigma} B^{\sigma}. \tag{2}$$

Amongst others, portfolio risk captures the probability of the government to default ($0 < \delta < 1$) and bond holdings are volatile $\sigma > 1$. Bonds are assumed to fall short of transactional benefits to the banking sector. They are, however, considered to offer an additional non-pecuniary benefit in the form of a regulatory advantage.

We assume both CBDCs and government bonds to qualify as high-quality liquid assets (HQLA), which improve the liquidity coverage ratio (LCR) as introduced by Basel III regulations (BCBS, 2013). The current liquidity regulation of the LCR refers to net cash outflows over the next 30 days, which requires a stock of HQLA to cover them, defined as

$$\text{LCR} = \frac{\text{Stock of HQLA}}{\text{Net cash outflows over the next 30 days}},$$

which is required to be equal to or larger than one. Regarding the numerator, CBDCs and bonds are both assumed to yield an additional non-pecuniary benefit to the banking sector – either to comply with imposed liquidity regulations or with portfolio preferences of the bank itself. In contrast to Meaning et al. (2018), we assume banks to actively manage the composition of their combined HQLA portfolio (see, e.g., Ihrig et al., 2019) in which CBDCs and bonds enter their portfolio jointly, instead of considering the additional non-pecuniary benefits of CBDCs and bonds separately. The outflows of short-term liabilities, as referred to in the denominator, include, among others, banks' retail deposits with less than 30 days maturity. In our model, we consider deposits as banks' only liabilities, to which an outflow probability of $0 < \alpha < 1$ is assigned as exogenously determined by current regulations.

In line with Juks (2018), we use a simplified proxy measure for the LCR and define liquidity as the difference between the actively managed HQLA portfolio and outflows of short-term liabilities. We reiterate that the management of the combined HQLA portfolio is assumed to offer a higher non-pecuniary benefit to the bank than its single components due to diversification effects resulting from different asset characteristics, such as default risk or convertibility. This liquidity measure is denoted by $\eta_L(C, B, D)$ and should, thus, be equal to or larger than zero. As an initial, intuitive formalization, let liquid asset management be given in CES functional form with

$$\eta_L(C, B, D) = \eta \left[\beta\sqrt{C} + (1-\beta)\sqrt{B}\right]^2 - \alpha D \tag{3}$$

where $\eta > 0, 0 < \alpha < 1, \beta < 1$ and an assumed constant elasticity of substitution equal to two.This specification is restrictive because of the conditions imposed on the cost structure.[4]

Banks are assumed to finance their asset side with liabilities in the form of deposits (D) on which they pay a deposit rate R^D. By contrast to Meaning et al. (2018), we do not assume bank deposits to default with probability γ, which applies in their model to both deposit demand and deposits supplied by banks. We assume a bank default probability to enter only the portfolio management of deposit holders and hence, exclude its own default probability in the bank's portfolio management.

Consequently the one-period portfolio optimization problem of the banking sector is assumed to be given by:

$$\begin{aligned} & \max_{C,B,D,L} V_b(C, B, D, L) \\ = \;& (1-\mu)R^L L - M(L) + (R^C + \phi^B)C \\ & +\eta_L(C, B, D) + R^B B - \sigma_B(B) - R^D D \\ s.t. \;:\; & \bar{w}_b = L + C + B - D \end{aligned} \tag{4}$$

3.2 The Non-Bank Private Sector

Consistent with the balance sheet in Table 2, the non-bank private sector receives loans from commercial banks. These allow non-banks to purchase real assets. In addition, we assume non-banks to hold financial assets in the form of commercial bank deposits, CBDCs and government bonds. In the following, we disaggregate the non-bank private sector into a representative household and representative investors.

[4] Future research might motivate banks' preferences for the HQLA portfolio by using a more microfounded risk-return framework, e.g., with the help of the Sharpe ratio to determine an optimal portfolio of riskier HQLA, which enters banks' complete HQLA portfolio depending on its risk aversion to determine the optimal share of risky assets for given risk-return trade-offs.

Representative Household For simplicity, we assume the reduced balance sheet of a representative household to be given by the following Table 3.

Table 3: Representative Household's Balance Sheet

Household (h)

Assets		Liabilities	
Deposits	D		
CBDCs	C		
Bonds	B	Net wealth	w_h

Households are thus assumed to hold risk-free CBDCs (C) where, again, each unit of CBDCs held provides a pecuniary benefit of R^C. Households also receive a non-pecuniary benefit of holding CBDCs in their portfolio as denoted by

$$\phi^C(C) = \phi\frac{1}{\upsilon}C^{\upsilon} \tag{5}$$

with $0 < \upsilon < 1$, which results from its transactional services as means of exchange. For instance, the non-bank private sector can benefit from lower transaction fees or more rapid cross-border payments.

In addition to CBDCs, households are assumed to hold commercial bank deposits (D), which yield a pecuniary return of R^D. Bank deposits offer an additional non-pecuniary benefit as means of exchange as given by

$$\phi^D(D) = \frac{1}{\phi}(1-\gamma)\frac{1}{\kappa}D^{\kappa} \tag{6}$$

with $0 < \kappa < 1$, allowing private agents, e.g., to pay online in domestic currency. By contrast to CBDCs, however, commercial banks are assumed to default with probability $0 < \gamma < 1$. Consequently, households hold two assets in the form of CBDCs and bank deposits for transaction purposes. By contrast to Meaning et al. (2018), we assume households to decide on the joint additional, non-pecuniary benefit offered by both electronic means of exchange (ϕ) as given by

$$\phi = \frac{\phi^C}{\phi^D}, \tag{7}$$

which denotes the non-pecuniary benefit provided by holding CBDCs relative to the associated benefit for bank deposits. We assume overall non-pecuniary benefits of holding electronic means of exchange to decline with increasing deposit holdings. This assumption is justified on the grounds of commercial bank deposits to be on average, e.g., slower than CBDCs regarding transaction and settlement speed of payments.

In addition to CBDCs and deposits, households are assumed to hold interest-bearing government bonds (B), which do not offer non-pecuniary benefits to the non-bank private sector. Bonds add to portfolio risk as denoted by Equation (2) above.

The household's end of period objective function is thus given by

$$\begin{aligned}\max_{C,D,B} V_h(C,D,B) &= R^C C + \phi^C(C) + (1-\gamma)R^D D + \phi^D(D) \\ &\quad + R^B B - \sigma_B(B) \\ s.t.\ \bar{w}_h &= C + D + B\end{aligned} \tag{8}$$

Representative Firm Production For simplicity, we assume a representative, profit maximizing firm $i \in F$ to produce its good Q_i with the help of a firm-owned stock of fixed assets (K), such as manufacturing equipment or production facilities. The neoclassical production function with diminishing marginal returns is assumed to be given by

$$Q_i = \epsilon K^{\epsilon} \tag{9}$$

where $0 < \epsilon < 1$. Production yields an internal rate of return on real capital denoted by $R^K(K)$, which is given by $R^K(K) = \epsilon K^{\epsilon-1}$. The firm is assumed to finance its business operation by costly bank credits (L) where the loan rate is denoted by R^L. For simplicity, we further assume that the firm not to be interested in holding financial assets.

The profit maximizing firm determines its investment in an optimal volume of real capital given costly credits.

$$\begin{aligned}\max_{L,K} \Pi_i(L,K) &= R^K(K)K - R^L L \\ &= \epsilon K^{\epsilon-1}K - R^L L \\ s.t. \bar{w}_i &= K - L\end{aligned} \tag{10}$$

The reduced balance sheet is illustrated in Table 4 where the firm's net worth is denoted by w_i. Overall net worth of the non-bank private sector is assumed to be given by $w_p = w_i + w_h$.

Table 4: Representative Firm's Balance Sheet

Firm (i)

Assets		Liabilities	
Real capital	K	Loans	L
		Net wealth	w_i

3.3 Assets: Demand and Supply Functions

Following the description of the single sectors' balance sheet composition, we will now focus on the determinants of the respective asset demand and supply functions. In the following subsection, subscripts will denote the associated sector, while superscripts denote if the variable of interest is demanded (d) or supplied (s).

Determinants of the Banking Sector's Portfolio From the bank's optimization problem, we can derive the bank's demand and loan supply functions as described in the following Lemma 1.

Lemma 1 *(Banking Sector's Demand and Supply Functions)*

The optimization problem given in Equation (4) and the respective F.O.C.s implicitly define the banking sector's asset demand and loan supply functions for the four groups of assets recorded in its balance sheet.

(i)	*CBDCs*	$C_b^D(\overset{(+)}{R^C}, \overset{(-)}{R^B}, \overset{(-)}{R^D}, \overset{(+)}{\eta}, \overset{(+)}{\phi^B}, \overset{(-)}{\alpha})$
(ii)	*Government bonds*	$B_b^D(\overset{(-)}{R^C}, \overset{(+)}{R^B}, \overset{(-)}{R^D}, \overset{(+)}{\eta}, \overset{(-)}{\alpha})$
(iii)	*Commercial bank deposits*	$D_b^S(\overset{(+)}{R^C}, \overset{(+)}{R^B}, \overset{(+)}{R^L}, \overset{(-)}{R^D}, \overset{(-)}{\alpha})$
(iv)	*Commercial bank loans*	$L_b^S(\overset{(+)}{R^L}, \overset{(-)}{R^D})$

For a proof, see Appendix A.2.

Qualitative dependencies are shown in brackets above the respective determinant where, e.g., $\frac{dC_b^D}{dR^C} > 0$ is denoted by $C_b^D(\overset{(+)}{R^C})$. As shown in Appendix A.2, e.g., a higher bond rate leads to an increased demand of government bonds by the banking sector, which is indicated by the plus sign above the bond rate. By contrast, if the deposit rate increases, banks have higher funding costs and, thus, demand less bonds.

Determinants of the Non-Bank Private Sector's Portfolio Based on the households' optimization problem and firms' investment behavior, we can derive the non-bank private sector's asset demand functions as described in Lemma 2 as follows.

Lemma 2 *(Non-Bank Private Sector's Asset Demand Functions)*

The optimization problem in Equation (8) and the respective F.O.C.'s implicitly define households' optimal asset demand functions for the three groups of assets (i) to (iii). The firm's optimal demand for loans (iv) is implicitly defined by the firm's optimization problem in Equation (10) and the respective F.O.C.'s.

(i)	*CBDCs*	$C_h^D(\overset{(+)}{R^C}, \overset{(-)}{R^B}, \overset{(-)}{R^D}, \overset{(+)}{\phi})$
(ii)	*Government bonds*	$B_h^D(\overset{(-)}{R^C}, \overset{(+)}{R^B}, \overset{(-)}{R^D})$
(iii)	*Commercial bank deposits*	$D_h^D(\overset{(-)}{R^C}, \overset{(-)}{R^B}, \overset{(+)}{R^D}, \overset{(-)}{\phi})$
(iv)	*Commercial bank loans*	$L_i^D(\overset{(-)}{R^L})$

For a proof, see Appendix A.3.

The notation is analogous to Lemma 1, where, e.g., $\frac{dC_h^D}{dR^C} > 0$ is denoted by $C_h^D(\overset{(+)}{R^C})$.

3.4 Markets: Financial Market System and Market Equilibrium

Asset demand and supply functions determined in Lemma (1) and (2) shape financial markets. The CBDC market is characterized by the central bank's CBDC supply, which is demanded by the banking sector and households.Thus, the market for CBDCs is given by $C_h^D + C_b^D = C^S$ as described in detail in Equation (11-i) of the financial market system below. The bond market has a similar design with bonds supplied by the sovereign and demanded by the banking sector as well as households. We assume the supply of bonds to be exogenously given $B_h^D + B_b^D = B^S$ (Equation (11-ii)). The deposit market is characterized by households' deposit demand, which is completely satisfied by banks' deposit supply, $D_h^D = D_b^S$.The full description of this market is summarized in financial market system Equation (11-iii). Commercial banks' loan supply fully meets the associated demand by investors in the non-bank private sector. Hence, the loan market is given by $L_i^D = L_b^S$ as described in Equation(11-iv). The complete system of financial markets can be summarized by Equation system (11).

$$
\begin{aligned}
&(i) && F_1 = C_h^D(\overset{(+)}{R^C}, \overset{(-)}{R^B}, \overset{(-)}{R^D}, \overset{(+)}{\phi}) + \\
& && \qquad C_b^D(\overset{(+)}{R^C}, \overset{(-)}{R^B}, \overset{(-)}{R^D}, \overset{(+)}{\eta}, \overset{(+)}{\phi^B}, \overset{(-)}{\alpha}) - C^S = 0 \\
&(ii) && F_2 = B_h^D(\overset{(-)}{R^C}, \overset{(+)}{R^B}, \overset{(-)}{R^D}) + B_b^D(\overset{(-)}{R^C}, \overset{(+)}{R^B}, \overset{(-)}{R^D}, \overset{(+)}{\eta}, \overset{(-)}{\alpha}) - B^S = 0 \\
&(iii) && F_3 = D_h^D(\overset{(-)}{R^C}, \overset{(-)}{R^B}, \overset{(+)}{R^D}, \overset{(-)}{\phi}) - D_b^S(\overset{(+)}{R^C}, \overset{(+)}{R^B}, \overset{(+)}{R^L}, \overset{(-)}{R^D}, \overset{(-)}{\alpha}) = 0 \\
&(iv) && F_4 = L_b^S(\overset{(+)}{R^L}, \overset{(-)}{R^D}) - L_i^D(\overset{(-)}{R^L}) = 0
\end{aligned}
\tag{11}
$$

The notation is analogous with Lemma 1 and Lemma 2. Those four markets determine the equilibrium vector of endogenous variables $(\tilde{C}^S, \tilde{R}^B, \tilde{R}^D, \tilde{R}^L)$ with each endogenous variable depending on the vector of exogenous variables $\left(R^C, \phi, \phi^B, \eta, \alpha\right)$.

Proposition 1 *(Market Equilibrium)*

The financial market system (11) implicitly defines a vector of equilibrium values of the

(i) quantity of CBDCs $\tilde{C}^S = \tilde{C}^S\left(R^C, \phi, \phi^B, \eta, \alpha\right)$

(ii) bond rate $\tilde{R}^B = \tilde{R}^B\left(R^C, \phi, \phi^B, \eta, \alpha\right)$

(iii) deposit rate $\tilde{R}^D = \tilde{R}^D\left(R^C, \phi, \phi^B, \eta, \alpha\right)$ *and*

(iv) credit rate $\tilde{R}^L = \tilde{R}^L\left(R^C, \phi, \phi^B, \eta, \alpha\right)$.

For a proof, see Appendix A.4.

This portfolio equilibrium was realized due the banking and non-bank private sector's portfolio decisions. Both sectors included CBDCs in their portfolio, based on associated return and non-pecuniary benefits. The optimal choice for portfolio diversification and transaction purposes have determined the market equilibrium. The following section will focus on portfolio adjustments following exogenous shocks.

4 Monetary Policy Transmission

This section has a closer look at the implications of our model on monetary policy transmission in the new framework with CBDCs. We solve the system in a comparative static analysis and begin with the effects on CBDC supply. We continue with the transmission to the deposit rate, the credit rate, and the bond rate. Following the analysis of the effectiveness of monetary policy transmission on interest rates, we show the effects on the fulfilment of regulatory liquidity requirements.

4.1 The Effectiveness of Monetary Policy

To maintain its primary objective of price stability, the ECB sets policy rates, while the central bank money supply endogenously adjusts to market forces. Currently, changes in the interest rate on electronic reserves are transmitted to other interest rates in financial markets. Next, financial markets hopefully pass-through changes in asset prices and interest rates via several channels to the real economy, finally affecting output and prices (see ECB (2011) for a schematic overview and, e.g., Boivin et al. (2011) for a more detailed description of transmission channels). The link between the policy rate and market rates has been less reliable and the transmission lag unpredictable in recent times (see, e.g., Gries and Mitschke (2021) for further details).

The effect of a digital euro on monetary policy transmission depends on the exact implementation mechanism (Fung and Halaburda, 2016). CBDCs are directly transferred from the central bank to end users or banks without further intermediation steps. Intuitively, this would enable the central bank to steer the real economy much more precisely and at a faster pace than in the current framework.

Since we excluded reserves from our model, the CBDC rate becomes the policy instrument of monetary policy. In a recession, the central bank would implement a countermeasure to mitigate the economic downturn and reduce the CBDC rate to maintain price stability. Although our model does not allow for quantifying the strength nor indicating the pace of the pass-through, it offers qualitative results on the transmission to further interest rates.

Our results point to a reduced CBDC supply, but also a transmission to all endogenous interest rates in the economy, i.e., a positive correlation between the policy rate and the deposit, credit, and bond rate. Besides the transmission of changes in the pecuniary costs and benefits of holding CBDCs, we study the effects of a change in the design of CBDCs. We suggest a positive correlation between the non-pecuniary benefits of CBDCs over deposit holdings and the three rates considered. The effects on the supply of CBDCs are ambiguous. By contrast, the non-pecuniary benefits of CBDC holdings for banks positively affect the supply of CBDCs, but do not show a significant effect on the deposit, credit, nor on the bond rate. In the following the effects are desribed in further detail.

Effects on CBDC Supply The results for the effects on CBDC supply are summarized in Proposition 2.

Proposition 2 *(Effects on CBDC Supply)*

(a) Policy rate shock: $\frac{dC^s}{dR^C} > 0$.

(b) The effect triggered by a shock from non-pecuniary benefits of electronic means of exchange depends on the relative size of the resulting effects in the CBDC and the deposit market. If the CBDC market reaction dominates the deposit market reaction, the correlation is positive, i.e. $\frac{dC^s}{d\phi} > 0$*. By contrast, if the deposit market reaction dominates the CBDC market reaction, the correlation is negative, i.e.* $\frac{dC^s}{d\phi} < 0$.

(c) Non-pecuniary benefits (banking sector) shock: $\frac{dC^s}{d\phi^B} > 0$.

For a proof, see Appendix A.5.

We assume a price rule for CBDCs, in which the central bank sets the policy rate and satisfies the quantity of CBDCs demanded by the private sector. Thus, CBDC supply adjusts endogenously to the given policy rate R^C. As CBDCs yield a positive return, an increase in the policy rate is found to lead to a higher quantity of CBDCs supplied (see Proposition 2 (a)). If the central bank is willing to issue CBDCs perfectly elastically according to demand, i.e., without a cap, collateral or, e.g., against government debt (cf. Barrdear and Kumhof, 2016; Kumhof and Noone, 2018), this may lead to a disintermediation of the banking sector, which is discussed below in Section 4.2 in further detail.

As shown in parts (b) and (c) of Proposition 2, the banking sector and the private sector show different reaction schemes regarding the design of CBDCs. While a change of the non-pecuniary benefits of banks holding CBDCs clearly indicates a positive correlation with CBDC supply, the effect for the non-bank private sector is ambiguous. Since the non-bank private sector can choose between holding CBDCs and holding bank deposits as a liquid asset, the reaction depends on which market reaction is the dominating force. If the reaction in the CBDC market dominates, a change in the non-pecuniary benefits of holding CBDCs relative to holding deposits and CBDC supply will be positively correlated. By contrast, if the effect on the deposit market dominates, a change in the non-pecuniary benefits of holding CBDCs relative to deposits will be negatively correlated with CBDC supply. In the absence of empirical data on CBDCs and their reaction to changes in non-pecuniary benefits, this question remains open and has to be determined empirically in the near future.

Transmission to Further Interest Rates In a first step, we find the CBDC rate to be able to influence interest rates and asset prices. Our results suggest a positive correlation between the CBDC rate and the deposit, loan, and bond rate. Given the universal access to CBDCs, however, the subsequence of affected markets following a monetary shock induced by the central bank can be changed. We assume the closest competition between interest-bearing CBDCs and commercial bank deposits, followed by lending rates and asset prices, which will be analyzed subsequently.

Effects on the Deposit Rate The results of the transmission to the deposit rate are summarized in Proposition 3.

Proposition 3 *(Effects on the Deposit Rate)*
(a) Policy rate shock: $\frac{dR^D}{dR^C} > 0$.
(b) Non-pecuniary benefits (non-bank private sector) shock: $\frac{dR^D}{d\phi} > 0$.
(c) Non-pecuniary benefits (banking sector) shock: $\frac{dR^D}{d\phi^B} = 0$.
For a proof, see Appendix A.6.

Given the CBDC and the deposit market are closest substitutes in our model, as both assets rather focus on liquidity than return characteristics, transmission to the commercial bank deposit rate is assumed to be relatively fast and strong. Referring to part (a) of Proposition 3, the results generally indicate a positive correlation between the CBDC and the deposit rate. This effect is reasonable, since a non-pass-through of an increase in the CBDC rate would, ignoring non-pecuniary benefits of holding CBDCs, initiate a substitution process, where end users withdraw deposit holdings and hold CBDCs instead. This can result in a reduction of bank funding, lending, and financial stability (see Section 4.2). By contrast, a reduction of the CBDC rate incentivizes the non-bank private sector to withdraw CBDCs and hold bank deposits instead. This provides higher funding to the banking sector and can result in higher bank lending. Both substitution effects will be stronger the easier the convertibility between CBDCs and bank deposit holdings is.

Depending on the convertibility between CBDCs and deposits as well as the availability and costs of other funding sources, the speed of the pass-through from changes of the CBDC rate to the deposit rate can vary. To prevent the major adverse effects of bank runs, a potential asymmetric speed of pass-through can be suggested with a rise in the CBDC rate leading to a faster adjustment of the deposit rate than a reduction. The introduction of CBDCs can potentially mitigate the effect in the current monetary framework where empirical evidence reveals deposit rates to be upwards-sticky and downwards-flexible (see, e.g., Driscoll and Judson (2013) for a study on the US).

The introduction of CBDCs, thus, directly affects bank funding costs due to the competition with bank deposits. In line with Meaning et al. (2018), we suggest that banks' sensitivity to changes in policy rates will probably increase, though depending on convertibility. This effect can generally strengthen the transmission of monetary policy.

In our model, we do not distinguish between the effects of positive and negative CBDC rates. However, it should be noted that interest-bearing CBDCs can alleviate the implementation of negative policy rates (Agarwal and Kimball, 2015; Bordo and Levin, 2017; Goodfriend, 2016; Rogoff, 2015) and lower the ELB if cash were to disappear (Camera, 2017). If this scenario is realized, negative interest rates can incur reputational risks for the central bank (Engert and Fung, 2017; Stevens, 2017).

In addition to the deposit rate, banks can also alter non-pecuniary benefits offered by deposits to mitigate their flightiness. The results of a variation in non-pecuniary benefits offered by both electronic means of exchange (ϕ) resemble to those of the deposit rate (cf. Proposition 3 (b)). Given the fact that the non-pecuniary benefits of CBDC holdings relative to deposit holdings is changed by the central bank (ϕ^C) or the banking sector (ϕ^D), an increase in the benefits of CBDCs (decrease in the benefits of deposits) would induce end users to withdraw bank deposits and rather hold CBDCs. Likewise, a reduction of the benefits of CBDCs (increase in the benefits of bank deposits) incentivize a shift from CBDCs towards deposits. Banks can, thus, reduce the likelihood of deposit withdrawals by increasing the non-pecuniary benefits of bank deposits. These can be an improvement of banks' services (Daavoodalhosseini, 2018), the provision of overdrafts or partial refunds if users pay via the banks' online banking, just to name a few. If the introduction of CBDCs incentivizes banks to offer different kinds of additional non-pecuniary benefits, competition among banks and heterogeneity in the banking sector can potentially increase as a side-effect. This, by contrast, can increase banks' risk-taking (Daavoodalhosseini, 2018), searching for riskier investments with higher expected yield, eventually strengthening the risk-taking channel of monetary policy (cf. Rajan, 2005).

From the banking sector's perspective, the introduction of CBDCs would be rather an imperfect, but closer substitute to central bank reserves than to deposits, which we abstract from in our model. Hence, according to our model, a change in the non-pecuniary benefits of CBDCs for banks (ϕ^B) does not affect the deposit rate (cf. Proposition 3 (c)).

However, the universal access to CBDCs implies the interbank market, in which currently electronic reserves are reallocated between banks, is no longer restricted to banks only. The private sector can trade CBDCs, too. Although non-banks will probably trade smaller amounts of CBDCs than reserves, at least in theory, universal access to CBDC markets can increase liquidity and competition (cf. Meaning et al., 2018).

Effects on the Credit Rate (Credit Channel) We now turn to the effects of monetary policy on the banking sector's credit provision. We assume loans not to be close substitutes for CBDCs, which slows down the transmission process, probably being passed through from deposit to loan rates. The results of the pass-through to credit rates are summarized in Proposition 4.

Proposition 4 *(Effects on the Credit Rate)*
(a) Policy rate shock: $\frac{dR^L}{dR^C} > 0$.
(b) Non-pecuniary benefits (non-bank private sector) shock: $\frac{dR^L}{d\phi} > 0$.
(c) Non-pecuniary benefits (banking sector) shock: $\frac{dR^L}{d\phi^B} = 0$.
For a proof, see Appendix A.7.

In line with the results for the deposit rate, our results show a positive correlation between a change in the CBDC rate and a change in the loan rate (cf. Proposition 4 (a)). For a given mark-up, an increase in the CBDC rate would lead banks to increase deposit rates, and, probably in order to offset higher funding costs, raise lending rates. Higher borrowing costs reduce credit demand of the non-bank private sector and investment in the economy.

Overall, higher funding costs can cut bank lending (see Duquerroy et al. (2020) for an empirical analysis of French banks). To keep the level of bank funding and, thus, lending, banks can provide additional services and non-pecuniary benefits associated with holding bank deposits as previously discussed. As analyzed for the deposit rate and shown in part (b) of Proposition 4, our results indicate changes in the non-pecuniary benefits offered by CBDCs relative to deposits to be positively correlated with the loan rate. Consequently, on the one hand, banks will increase the lending rate if the non-pecuniary benefits of CBDCs increase. An increase of the non-pecuniary benefits of holding deposits, on the other hand, allows them to reduce the credit rate. Banks can offer a bundle of additional services connected with deposit holdings as well as credit provision, such as mortgage finance or financial advice on real estate financing. This higher non-pecuniary benefit of holding bank deposits instead of CBDCs reduces the ratio (ϕ) and, thus, leads to lower credit rates.

As noted above, our model indicates zero effect of a change in the non-pecuniary benefits of holding CBDCs for the banking sector itself, which holds also true for the credit rate (cf. Proposition 4 (c)).

In line with Meaning et al. (2018), we, thus, find the credit channel (see Bernanke and Gertler (1989) for a detailed description) to be still effectively operating following the introduction of CBDCs. The extent of the pass-through, however, depends crucially on the interconnectedness between deposit and loan markets. If increased funding costs make banks more sensitive to changes in the policy rate, the credit channel will be strengthened (cf. Meaning et al., 2018). Furthermore, universal access to CBDCs might increase competition in the credit market, which can reduce previous financial market imperfections and further strengthen this channel. By contrast, a reduction in banks' net interest margins (Meaning et al., 2018) and the amount of bank lending can weaken the overall importance of this channel (Armelius et al., 2018).

Effects on the Bond Rate (Asset Price Channel) Finally, we refer to the effects of a monetary policy impulse on the government bond rate as a representative asset. In line with Aiste et al. (2019) and CPMI-MC (2018), we note that the effects on the bond rate are much less clear than those previously discussed on the deposit and loan rates. The results are summarized in the following Proposition 5.

Proposition 5 *(Effects on the Bond Rate)*
(a) Policy rate shock: $\frac{dR^B}{dR^C} > 0$.
(b) Non-pecuniary benefits (non-bank private sector) shock: $\frac{dR^B}{d\phi} > 0$.
(c) Non-pecuniary benefits (banking sector) shock: $\frac{dR^B}{d\phi^B} = 0$.
For a proof, see Appendix A.8.

Referring to part (a) of Proposition 5, our results indicate a positive correlation between changes in the CBDC rate and changes in the bond rate. Assuming the relation $P^B = \frac{1}{R^B}$ holds, a decreasing policy rate decreases bond rates and increases bond prices. This suggests a transmission mechanism similar to the current asset price channel, according to which a decreasing policy rate increases asset prices, supporting investments and the demand for real and financial assets, which increases wealth and in turn consumption and investment spending (Modigliani, 1971). Since government bonds can also be used as loan collateral, banks' willingness to lend can increase with increasing collateral value.

Likewise, a change in the non-pecuniary benefits of holding CBDCs relative to bank deposits is positively correlated with the bond rate (Proposition 5 (b)). A higher non-pecuniary benefit of CBDCs relative to deposits would lead to higher bond rates and lower bond prices. If the banking sector increases the non-pecuniary benefits of holding bank deposits, bond rates will decrease and bond prices increase. By contrast, a change in the non-pecuniary benefits of CBDCs offered to the banking sector leaves the bond rate unaffected (Proposition 5 (c)).

Thus, our results confirm a potential strengthening of the monetary policy transmission with the most direct effect from the policy rate to the deposit rate. Depending on the competition and substitution between CBDCs and bank deposits, bank lending can be reduced. Further, the policy impulse is passed through to the lending rate and the bond rate. In addition, our results confirm the ECB's (2020) suggestion according to which banks can respond to the threat of losing bank funding by offering additional services and non-pecuniary benefits to deposit holders.

4.2 The LCR and Financial Stability

If the introduction of CBDCs causes a deposit flight, a large reduction in bank funding via deposits and a replacement with other liabilities will also have consequences for the ability of banks to fulfil regulatory liquidity requirements (Juks, 2018). In line with Juks (2018), we have defined liquidity as given by the difference between HQLA and outflows of short-term liabilities.

Outflows of short-term liabilities include, among others, banks' retail deposits with less than 30 days maturity. Current regulations consider these as rather sticky with "stable" deposits weighted with a 5 percent run-off rate, those deposits falling under the deposit insurance scheme even less with a 3 percent outflow probability. The introduction of CBDCs can potentially change this assumption with higher deposit outflows during times of distress (Juks, 2018).

In our model, we consider retail deposits as banks' only liabilities. Following a regulatory change of the run-off rate, our model shows a positive correlation with the deposit and loan rate, which is summarized in Proposition 6.

Proposition 6 *(Effects of the Run Off-Rate)*
(a) Effect on the deposit rate: $\frac{dR^D}{d\alpha} > 0$.
(b) Effect on the credit rate: $\frac{dR^L}{d\alpha} > 0$.
For a proof, see Appendix A.9.

In line with Andolfatto (2018) and Mancini-Griffoli et al. (2018), our results indicate a higher probability of deposit outflows to induce banks to increase the deposit rate in order to maintain banks' level of funding from the non-bank private sector. Alternative proposals in the literature refer to a replacement of lost deposits with other liabilities, such as bond issuance (Juks, 2018) or refinancing from the central bank (Brunnermeier and Niepelt, 2019; Mancini-Griffoli et al., 2018; Meaning et al., 2018; Pfister, 2017). These approaches referring to a substitution in bank funding could be evaluated by a model extension. If banks refrain from increasing deposits rates, banks may have to reduce their balance sheet, including bank lending, which imposes a risk of disintermediation by the banking sector and thus, a risk to financial stability.

In addition to the alternative approaches for maintaining deposit funding, our results indicate a potential risk mitigation by a higher efficiency of HQLA portfolio management, i.e., the bank's liquidity portfolio of bonds and CBDC holdings. Regarding the efficiency of the HQLA portfolio management, our model shows a negative correlation with both, the deposit and credit rate as summarized in Proposition 7.

Proposition 7 *(Effects of the Efficiency of HQLA Portfolio Management)*
(a) Effect on the deposit rate: $\frac{dR^D}{d\eta} < 0$.
(b) Effect on the credit rate: $\frac{dR^L}{d\eta} < 0$.
For a proof, see Appendix A.10.

A more efficient portfolio management can thus potentially counteract the effects stemming from a higher probability of deposit outflows and reduce bank funding costs.

Overall, the results confirm our hypothesis of increased bank funding costs following the introduction of the digital euro. This effect, however, might be mitigated by a more efficient management of the HQLA portfolio.

5 Discussion and Policy Implications

In the following section, we take a closer look at wider implications of our model on monetary and macroprudential policies. Our results indicate monetary policy to be effective in a new policy framework including interest-bearing CBDCs. However, we have also identified risks as well as requirements to safeguard effective monetary policy transmission and financial stability.

Overall, the central bank should safeguard the trust in money (cf. ECB, 2020). By issuing universally accessible CBDCs, the central bank competes, on the one hand, with private sector solutions, such as Bitcoins or stablecoins. CBDCs can crowd out the usage of crypto assets as mediums of exchange and strengthen the effectiveness of monetary policy and financial stability in the domestic economy (cf. Zhu and Henry, 2019). This depends, however, on the intrinsic features of the digital euro as means of payment and store of value, where eventually an improvement of the current payment system (cf. Bofinger and Haas, 2021) or an (international) cooperation on the regulation of private sector solutions can lead to similar results.

The central bank competes, on the other hand, with the domestic banking sector in holding non-bank private sector deposits. Interest-bearing CBDCs, however, have the comparative advantage of an unlimited, risk-free central bank liability. Currently, the banking sector suffers from very low or even negative interest rates, reducing net profit margins and bank capital. If the banking sector is further weakened, banks' credit supply and economic activity can be significantly reduced. There are two options to prevent a disintermediation of the banking sector. Either the central bank can reduce the attractiveness of CBDCs, or the banking sector can increase the attractiveness of holding bank deposits.

To prevent sudden and excessive flights from bank deposits into CBDCs, the central bank can, e.g., restrict the exchange between CBDCs and deposits. Alternatively, a general limit on holding digital euros can be introduced. These options are, however, both excluded by the ECB (2020). Alternatively, a general limit on holding digital euros can be introduced. The ECB (2020) proposes a quantitative limit for holding bearer digital euros, which can be extended to account-based digital euro holdings (Bindseil, 2020). Further approaches in the literature suggest, for instance, a tiered remuneration system (Bindseil, 2020), CBDC issuance only against eligible securities (Kumhof and Noone, 2018), or charging fees on CBDC accounts and associated services (Armelius et al., 2018). The banking sector, in turn, can provide additional non-pecuniary benefits with the purpose of deposit holdings remaining at commercial banks.

Further, LCR regulations should be reconsidered regarding a reduced stickiness of deposits after CBDC introduction (see also Juks, 2018). In addition, the effects of the introduction of an on-demand exchangeable HQLA in the form of CBDCs should be explored in further detail.

The shift of bank deposits to the central bank implies a transfer of payment data and customer information from the banking sector to the central bank. This can negatively affect banks' risk assessment capacity and, thus, bank risk in general. A centralized database, to which banks have on-demand access can eventually mitigate associated risks. However, further organizational challenges regarding the implementation of the digital euro remain a priority.

6 Concluding Remarks

This study has surveyed and interpreted key properties of different kinds of money and money-like assets as means of payment and store of value as well as resulting trade-offs, which affect portfolio choices of the banking and the non-bank private sector.

Further, the paper shed light on distinct features in which the design of CBDCs can be varied in general, before turning to the specific properties of the digital euro initiative. In a comparison of the suggested concepts' characteristics, a bearer digital euro offers a higher level of anonymity, which is valued the most according to the ECB (2021) survey and probably allows the central bank to offer a lower pecuniary return on digital euro holdings.

To analyze the effectiveness of monetary policy, we have refined and closed the arbitrage model of Meaning et al. (2018), including interest-bearing retail CBDCs in a portfolio model. Our main results indicate the transmission of monetary policy to be effective following the introduction of the digital euro. A variation in the policy rate is passed through to deposit and loan rates as well as to bond prices. Although our model does not allow for drawing conclusions on the speed nor the strength of the pass-through, we suggest a strengthened pass-through given the more direct implementation of monetary policy. Further, our model confirms the ECB's (2020) hypothesis claiming that banks can reduce deposit withdrawals by increasing non-pecuniary benefits and services for deposit holders.

As interest-bearing CBDCs directly compete with bank deposits, resulting substitution effects can affect financial stability. Regarding banks' ability to fulfill regulatory liquidity requirements, our results indicate a higher deposit run-off rate to increase bank funding costs. This effect can, however, eventually be mitigated by a more efficient portfolio management of HQLA. We therefore suggest constraining the exchange between CBDCs and bank deposits and reconsidering current liquidity regulations.

This paper adds to the rapidly growing literature on CBDCs and offers early insights with many questions remaining unanswered. Future research can provide model extensions regarding, e.g., the inclusion of the central bank balance sheet, additional liabilities of the banking sector to replace lost deposits, or explicit modeling of money-like assets auch as Bitcoins and stablecoins. The strength and pass-through of the transmission remain open as to be tested empirically in the future. Moreover, to understand how the features of CBDCs as means of payment and store of value affect the economy, it is crucial to further explore and empirically study the preferences and portfolio choices of the non-bank private sector, determining the demand of CBDCs. In line with this research, the survey of the ECB (2021) is regarded as a reasonable first step.

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Appendix

A.1 Comparison of Account-Based and Bearer Digital Euro

According to Meaning et al. (2018), the no-arbitrage condition between a theoretical risk-free rate (R) and CBDCs is given by

$$R = R^C + \phi^C$$

with R^C denoting the interest rate on CBDC holdings and ϕ^C as non-pecuniary benefits of CBDCs.

We split up the non-pecuniary benefits of an account-based (ϕ^{CA}) and a token-based CBDC (ϕ^{CT}) offered to the non-bank private sector by three arbitrarily chosen categories of (i) privacy, data protection, anonymous transactions, (ii) average transaction speed and settlement, and (iii) range (geographical, number of users). Assuming a similar speed and range of transactions for both CBDCs but a higher level of privacy offered by a token-based CBDC, the expected return from a unit of a bearer digital euro as given in Equation (13) is higher than the return from an account-based CBDC as given by Equation (12).

$$R = R^{CA} + \phi^{CA} \tag{12}$$

$$R = R^{CT} + \phi^{CT} \tag{13}$$

Conclusion 1 *Given no-arbitrage between the two possibly co-existing versions of CBDCs, higher non-pecuniary benefits to end-users of a bearer digital euro allow the central bank to pay a lower interest rate on the bearer than on the account-based version.*

$$\begin{array}{ccc} \phi^{CA} & < & \phi^{CT} \\ R^{CA} & > & R^{CT} \end{array}$$

A.2 Proof of Lemma 1

The banking sector's demand and supply functions are derived from the portfolio choice model.

Optimization problem

$$\begin{aligned}
& & \max_{C,B,D,L} V_b(L,C,B,D) \\
& = & (1-\mu)R^L L - M(L) + (R^C+\phi^B)C + \eta_L(C,B,D) \\
& & +R^B B - \sigma_B(B) - R^D D \\
s.t. & : & \bar{w}_b = L + C + B - D
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_b &= (R^C+\phi^B)C + \eta_L(C,B,D) + R^B B - \sigma_B(B) + (1-\mu)R^L L \\
& \quad -M(L) - R^D D + \lambda_b(w_b + D - C - L - B) \\
&= (R^C+\phi^B)C + \eta\left[\beta^2 C + 2\beta(1-\beta)(CB)^{1/2} + (1-\beta)^2 B - \alpha D\right] \\
& \quad +R^B B - \delta\frac{1}{\sigma}B^\sigma + (1-\mu)R^L L - \frac{1}{\tau}L^{\tau-1} - R^D D \\
& \quad +\lambda_b(w_b + D - C - L - B)
\end{aligned}$$

F.O.C.s

$$\begin{aligned}
(i)\ \ G_1 &= \frac{d\mathcal{L}_b}{dC} = (R^C+\phi^B) + \frac{d(\eta_L(C,B,D))}{dC} - \lambda_b \\
&= R^C + \phi^B + \eta\left(\beta^2 + \beta(1-\beta)\left(\frac{B}{C}\right)^{1/2}\right) - \lambda_b = 0 \\
(ii)\ \ G_2 &= \frac{d\mathcal{L}_b}{dB} = R^B + \frac{d(\eta_L(C,B,D))}{dB} - \frac{d(\sigma_B(B))}{dB} - \lambda_b \\
&= R^B + \eta\left(\beta(1-\beta)\left(\frac{C}{B}\right)^{1/2} + (1-\beta)^2\right) - \delta B^{\sigma-1} - \lambda_b = 0 \\
(iii)\ \ G_3 &= \frac{d\mathcal{L}_b}{dL} = (1-\mu)R^L - \frac{d(M(L))}{dL} - \lambda_b \\
&= (1-\mu)R^L - L^{\tau-1} - \lambda_b = 0 \\
(iv)\ \ G_4 &= \frac{d\mathcal{L}_b}{dD} = -R^D - \alpha + \lambda_b = 0 \\
(v)\ \ G_5 &= \frac{d\mathcal{L}_b}{d\lambda_b} = w_b + D - C - B - L = 0
\end{aligned}$$

Implicit Function Theorem To show the existence of a solution to the system, we use the implicit function theorem. We take the total derivative and rewrite the system in matrix notation.

$$
\begin{pmatrix}
\overset{(-)}{\frac{\partial G_1}{\partial C}} & \overset{(+)}{\frac{\partial G_1}{\partial B}} & 0 & 0 & -1 \\
\overset{(+)}{\frac{\partial G_2}{\partial C}} & \overset{(-)}{\frac{\partial G_2}{\partial B}} & 0 & 0 & -1 \\
0 & 0 & \overset{(-)}{\frac{\partial G_3}{\partial L}} & 0 & -1 \\
0 & 0 & 0 & 0 & 1 \\
-1 & -1 & -1 & +1 & 0
\end{pmatrix}
\begin{pmatrix} dC \\ dB \\ dL \\ dD \\ d\lambda_b \end{pmatrix}
$$

$$
= \begin{pmatrix}
-1dR^C - 1d\phi^B - \left[\beta^2 + 2\beta(1-\beta)B^{1/2}(\frac{1}{2})C^{-1/2}\right] d\eta \\
-dR^B - \left[\beta^2 + 2\beta(1-\beta)B^{1/2}(\frac{1}{2})C^{-1/2}\right] d\eta \\
-(1-\mu)\, dR^L \\
+1dR^D + 1d\alpha \\
-dw_b
\end{pmatrix}
$$

In order to apply the implicit function theorem, we have to show that the Jacobian of the system is different to zero, i.e. $|J| \neq 0$

$$
\begin{aligned}
|J| &= \begin{vmatrix}
\overset{(-)}{\frac{\partial G_1}{\partial C}} & \overset{(+)}{\frac{\partial G_1}{\partial B}} & 0 & 0 & -1 \\
\overset{(+)}{\frac{\partial G_2}{\partial C}} & \overset{(-)}{\frac{\partial G_2}{\partial B}} & 0 & 0 & -1 \\
0 & 0 & \overset{(-)}{\frac{\partial G_3}{\partial L}} & 0 & -1 \\
0 & 0 & 0 & 0 & +1 \\
-1 & -1 & -1 & +1 & 0
\end{vmatrix} \\
&= \begin{vmatrix}
\overset{(-)}{G_{11}} & \overset{(+)}{G_{12}} & 0 & 0 & -1 \\
\overset{(+)}{G_{21}} & \overset{(-)}{G_{22}} & 0 & 0 & -1 \\
0 & 0 & \overset{(-)}{G_{33}} & 0 & -1 \\
0 & 0 & 0 & 0 & +1 \\
-1 & -1 & -1 & +1 & 0
\end{vmatrix} \\
&= -\left[\overset{(-)}{G_{11}}\overset{(-)}{G_{22}}\overset{(-)}{G_{33}} - \overset{(-)}{G_{33}}\overset{(+)}{G_{21}}\overset{(+)}{G_{12}} \right] > 0
\end{aligned}
$$

The last line holds since we generally assume that direct (own) effects as given by G_{ij} with $i = j$ dominate cross effects (G_{ij} with $i \neq j$). This yields $|J| \neq 0$ and the system has an implicit solution.

Cramer's Rule The system's solution, i.e., the banking sector's portfolio adjustments to changes in exogenous variables ($R^C, R^B, R^L, R^D, \phi^B, \eta, \alpha$), can be derived by using Cramer's rule, which can be applied if $|J| \neq 0$. We do not go through this procedure for every single variable, but calculate as an example the banking sector's adjustment of CBDC holdings to exogenous shocks denoted by $\triangle$.

$$
\begin{aligned}
|J_{1R^C}| &= \begin{vmatrix} \triangle & \overset{(+)}{G_{12}} & 0 & 0 & -1 \\ 0 & \overset{(-)}{G_{22}} & 0 & 0 & -1 \\ 0 & 0 & \overset{(-)}{G_{33}} & 0 & -1 \\ 0 & 0 & 0 & 0 & +1 \\ 0 & -1 & -1 & +1 & 0 \end{vmatrix} \\
&= (-\triangle)\left(\overset{(-)}{G_{22}}\overset{(-)}{G_{33}}\right) > 0 \quad \text{with } \triangle = -1 \\
\frac{dC}{dR^C} &= \frac{|J_{1R^C}|}{|J|} > 0
\end{aligned}
$$

$$
\begin{aligned}
|J_{1R^B}| &= \begin{vmatrix} 0 & \overset{(+)}{G_{12}} & 0 & 0 & -1 \\ \triangle & \overset{(-)}{G_{22}} & 0 & 0 & -1 \\ 0 & 0 & \overset{(-)}{G_{33}} & 0 & -1 \\ 0 & 0 & 0 & 0 & +1 \\ -1 & -1 & -1 & +1 & 0 \end{vmatrix} \\
&= -\left(\triangle\overset{(-)}{G_{33}}\overset{(+)}{G_{12}}\right) < 0 \quad \text{with } \triangle = -1 \\
\frac{dC}{dR^B} &= \frac{|J_{1R^B}|}{|J|} < 0
\end{aligned}
$$

$$
\begin{aligned}
|J_{1R^D}| &= \begin{vmatrix} 0 & \overset{(+)}{G_{12}} & 0 & 0 & -1 \\ 0 & \overset{(-)}{G_{22}} & 0 & 0 & -1 \\ 0 & 0 & \overset{(-)}{G_{33}} & 0 & -1 \\ \triangle & 0 & 0 & 0 & +1 \\ 0 & -1 & -1 & +1 & 0 \end{vmatrix} \\
&= (-\triangle)\left(\overset{(-)}{G_{22}}\overset{(-)}{G_{33}} - \overset{(-)}{G_{33}}\overset{(+)}{G_{12}}\right) < 0 \quad \text{with } \triangle = 1 \\
\frac{dC}{dR^D} &= \frac{|J_{1R^D}|}{|J|} < 0
\end{aligned}
$$

$$
\begin{aligned}
|J_{1\phi^B}| &= \begin{vmatrix} \triangle & \overset{(+)}{G_{12}} & 0 & 0 & -1 \\ 0 & \overset{(-)}{G_{22}} & 0 & 0 & -1 \\ 0 & 0 & \overset{(-)}{G_{33}} & 0 & -1 \\ 0 & 0 & 0 & 0 & +1 \\ 0 & -1 & -1 & +1 & 0 \end{vmatrix} \\
&= (-\triangle)\left(\overset{(-)}{G_{22}}\overset{(-)}{G_{33}}\right) > 0 \ \text{ with } \triangle = -1 \\
\frac{dC}{d\phi^B} &= \frac{\left|J_{1\phi^B}\right|}{|J|} > 0
\end{aligned}
$$

$$
\begin{aligned}
|J_{1\eta}| &= \begin{vmatrix} \triangle_1 & \overset{(+)}{G_{12}} & 0 & 0 & -1 \\ \triangle_2 & \overset{(-)}{G_{22}} & 0 & 0 & -1 \\ 0 & 0 & \overset{(-)}{G_{33}} & 0 & -1 \\ 0 & 0 & 0 & 0 & +1 \\ 0 & -1 & -1 & +1 & 0 \end{vmatrix} \\
&= (-1)\left(\triangle_1\overset{(-)}{G_{22}}\overset{(-)}{G_{33}} - \overset{(-)}{G_{33}}\triangle_2\overset{(+)}{G_{12}}\right) > 0 \\
\text{with } \triangle_1 &= < 0, \triangle_2 =< 0 \\
\frac{dC}{d\eta} &= \frac{|J_{1\eta}|}{|J|} > 0
\end{aligned}
$$

$$
\begin{aligned}
|J_{1\alpha}| &= \begin{vmatrix} 0 & \overset{(+)}{G_{12}} & 0 & 0 & -1 \\ 0 & \overset{(-)}{G_{22}} & 0 & 0 & -1 \\ 0 & 0 & \overset{(-)}{G_{33}} & 0 & -1 \\ \triangle & 0 & 0 & 0 & +1 \\ 0 & -1 & -1 & +1 & 0 \end{vmatrix} \\
&= \triangle\left(-\overset{(-)}{G_{22}}\overset{(-)}{G_{33}} + \overset{(-)}{G_{33}}\overset{(+)}{G_{12}}\right) < 0 \ \text{ with } \triangle = 1 \\
\frac{dC}{d\alpha} &= \frac{|J_{1\alpha}|}{|J|} < 0
\end{aligned}
$$

The demand functions of the other assets are derived in the same way.

A.3 Proof of Lemma 2

The non-bank private sector's demand and supply functions are derived from the portfolio choice model.

Representative Firm

Optimization problem

$$\begin{aligned} \max_{L,K} \Pi_i(L,K) &= V_i(L,K) = R^K(K)K - R^L L \\ s.t. \bar{w}_i &= K - L \end{aligned}$$

$$\mathcal{L}_i = \epsilon K^{\epsilon} - R^L L + \lambda_i(\bar{w}_i - K + L)$$

F.O.C.s

$$\begin{aligned} (i) \;\; E_1 &= \frac{d\mathcal{L}_i}{dK} = \epsilon^2 K^{\epsilon-1} - \lambda_i = 0 \Longleftrightarrow K = \left(\frac{\lambda_i}{\epsilon^2}\right)^{\frac{1}{\epsilon-1}} \\ (ii) \;\; E_2 &= \frac{d\mathcal{L}_i}{dL} = -R^L + \lambda_i = 0 \Longleftrightarrow \lambda_i = R^L \\ (iii) \;\; E_3 &= \frac{d\mathcal{L}_i}{d\lambda_i} = \bar{w}_i - K + L = 0 \end{aligned}$$

plug in (ii) in (i) yields

$$L^D(\overset{(-)}{R^L}) = K^D(\overset{(-)}{R^L}) = \left(\frac{1}{\epsilon^2} R^L\right)^{\frac{1}{\epsilon-1}}$$

Representative Household

Optimization problem

$$\begin{aligned} \max_{C,B,D} V_h(C,B,D) &= R^C C + \phi^C(C) + R^B B - \sigma_B(B) \\ &\quad +(1-\gamma)R^D D + \phi^D(D) \\ s.t. \bar{w}_h &= C + B + D \end{aligned}$$

$$\begin{aligned} \mathcal{L}_h &= \Big(R^C C + \phi^C(C)\Big) + \big(R^B B - \sigma_B(B)\big) \\ &\quad +(1-\gamma)R^D D + \phi^D(D) + \lambda_h(\bar{w}_h - C - B - D) \end{aligned}$$

F.O.C.s

$$
\begin{aligned}
(i)\ \ A_1 &= \frac{d\mathcal{L}_h}{dC} = R^C + \frac{d(\phi^C(C))}{dC} - \lambda_h = R^C + \phi C^{\upsilon-1} - \lambda_h = 0 \\
(ii)\ \ A_2 &= \frac{d\mathcal{L}_h}{dB} = R^B - \frac{d\sigma_B(B)}{dB} - \lambda_h = R^B - \delta B^{\sigma-1} - \lambda_h = 0 \\
(iii)\ \ A_3 &= \frac{d\mathcal{L}_h}{dD} = (1-\gamma)R^D + \frac{d(\phi^D(D))}{dD} - \lambda_h \\
&= (1-\gamma)R^D + (1-\gamma)\frac{1}{\phi}D^{\kappa-1} - \lambda_h = 0 \\
(iv)\ \ A_4 &= \frac{d\mathcal{L}_h}{d\lambda_h} = w_h - C - D - B = 0
\end{aligned}
$$

Implicit Function Theorem To show the existence of a solution to the system, we use the implicit function theorem.

We take the total derivative and rewrite the system in matrix notation:

$$
\begin{pmatrix}
\overset{(-)}{\frac{\partial A_1}{\partial C}} & 0 & 0 & -1 \\
0 & \overset{(-)}{\frac{\partial A_2}{\partial B}} & 0 & -1 \\
0 & 0 & \overset{(-)}{\frac{\partial A_3}{\partial D}} & -1 \\
-1 & -1 & -1 & 0
\end{pmatrix}
\begin{pmatrix}
dC \\ dB \\ dD \\ d\lambda_h
\end{pmatrix}
=
\begin{pmatrix}
-dR^C - \left(C^{\upsilon-1}\right)d\phi \\
-dR^B \\
-(1-\gamma)\,dR^D + \left((1-\gamma)\,D^{\kappa-1}\frac{1}{\phi^2}\right)d\phi \\
-dw_h
\end{pmatrix}
$$

By analogy with Lemma 1, we have to show that the Jacobian of the system is different to zero, i.e. $|J| \neq 0$ and find:

$$
\begin{aligned}
|J| &= \begin{vmatrix} \overset{(-)}{\frac{\partial A_1}{\partial C}} & 0 & 0 & -1 \\ 0 & \overset{(-)}{\frac{\partial A_2}{\partial B}} & 0 & -1 \\ 0 & 0 & \overset{(-)}{\frac{\partial A_3}{\partial D}} & -1 \\ -1 & -1 & -1 & 0 \end{vmatrix} \\
&= \begin{vmatrix} \overset{(-)}{A_{11}} & 0 & 0 & -1 \\ 0 & \overset{(-)}{A_{22}} & 0 & -1 \\ 0 & 0 & \overset{(-)}{A_{33}} & -1 \\ -1 & -1 & -1 & 0 \end{vmatrix} \\
&= -\overset{(-)}{A_{11}}\overset{(-)}{A_{33}} - \overset{(-)}{A_{11}}\overset{(-)}{A_{22}} - \overset{(-)}{A_{22}}\overset{(-)}{A_{33}} < 0
\end{aligned}
$$

Cramer's Rule By analogy with the proof of Lemma 1, we exemplary calculate the non-bank private sector's adjustment of CBDC holdings for exogenous shocks and find with the help of Cramer's rule:

$$
\begin{aligned}
|J_{1R^C}| &= \begin{vmatrix} \triangle & 0 & 0 & -1 \\ 0 & \overset{(-)}{A_{22}} & 0 & -1 \\ 0 & 0 & \overset{(-)}{A_{33}} & -1 \\ 0 & -1 & -1 & 0 \end{vmatrix} \\
&= \overset{(-)}{A_{33}} + \overset{(-)}{A_{22}} < 0 \quad \text{with } \triangle = -1 \\
\frac{dC}{dR^C} &= \frac{|J_{1R^C}|}{|J|} > 0
\end{aligned}
$$

$$
\begin{aligned}
J_{1R^B} &= \begin{vmatrix} 0 & 0 & 0 & -1 \\ \triangle & \overset{(-)}{A_{22}} & 0 & -1 \\ 0 & 0 & \overset{(-)}{A_{33}} & -1 \\ 0 & -1 & -1 & 0 \end{vmatrix} \\
&= -\triangle\left(-\overset{(-)}{A_{33}}\right) > 0 \;\; \text{with } \triangle = -1 \\
\frac{dC}{dR^B} &= \frac{|J_{1R^B}|}{|J|} < 0
\end{aligned}
$$

$$
\begin{aligned}
J_{1R^D} &= \begin{vmatrix} 0 & 0 & 0 & -1 \\ 0 & \overset{(-)}{\frac{\partial A_2}{\partial B}} & 0 & -1 \\ \triangle & 0 & \overset{(-)}{\frac{\partial A_3}{\partial D}} & -1 \\ 0 & -1 & -1 & 0 \end{vmatrix} \\
&= \triangle \overset{(-)}{\frac{\partial A_2}{\partial B}} > 0 \quad \text{with } \triangle = -(1-\gamma) < 0 \\
\frac{dC}{dR^D} &= \frac{|J_{1R^D}|}{|J|} < 0
\end{aligned}
$$

$$
\begin{aligned}
|J_{1\phi}| &= \begin{vmatrix} \triangle_1 & 0 & 0 & -1 \\ 0 & \overset{(-)}{A_{22}} & 0 & -1 \\ \triangle_3 & 0 & \overset{(-)}{A_{33}} & -1 \\ 0 & -1 & -1 & 0 \end{vmatrix} \\
&= \triangle_1 \left(-\overset{(-)}{A_{33}} - \overset{(-)}{A_{22}} \right) + \triangle_3 \left(\overset{(-)}{A_{22}} \right) < 0 \\
\text{with } \triangle_1 &= -\left(C^{v-1} \right) < 0,\ \triangle_3 = \left((1-\gamma)\, D^{\kappa-1} \frac{1}{\phi^2} \right) > 0 \\
\frac{dC}{d\phi} &= \frac{|J_{1\phi}|}{|J|} > 0
\end{aligned}
$$

The demand functions of the other assets are derived in the same way.

A.4 Financial Market System and Equilibrium

Proof. Equilibrium price vector, derived using the implicit function theorem:

From the financial market system (11), we obtain a system of four functions $F_1, ..., F_4$ depending on four endogenous variables C^S, R^B, R^D, and R^L. To ensure the existence of an equilibrium price vector, we apply the implicit function theorem to the financial market system, which requires $|J| \neq 0$. By analogy with the previous proofs the Jacobian can be derived as given by:

$$
\begin{aligned}
J &= \begin{pmatrix}
-1 & \overset{(-)}{\frac{\partial C_h^D}{\partial R^B}} + \overset{(-)}{\frac{\partial C_b^D}{\partial R^B}} & \overset{(-)}{\frac{\partial C_h^D}{\partial R^D}} + \overset{(-)}{\frac{\partial C_b^D}{\partial R^D}} & 0 \\
0 & \overset{(+)}{\frac{\partial B_h^D}{\partial R^B}} + \overset{(+)}{\frac{\partial B_b^D}{\partial R^B}} & \overset{(-)}{\frac{\partial B_h^D}{\partial R^D}} + \overset{(-)}{\frac{\partial B_b^D}{\partial R^D}} & 0 \\
0 & \overset{(-)}{\frac{\partial D_h^D}{\partial R^B}} - \overset{(+)}{\frac{\partial D^S}{\partial R^B}} & \overset{(+)}{\frac{\partial D_h^D}{\partial R^D}} - \overset{(-)}{\frac{\partial D_b^S}{\partial R^D}} & -\overset{(+)}{\frac{\partial D_b^S}{\partial R^L}} \\
0 & \overset{(0)}{\frac{\partial L_b^S}{\partial R^B}} & \overset{(-)}{\frac{\partial L_b^S}{\partial R^D}} & \overset{(+)}{\frac{\partial L_b^S}{\partial R^L}} - \overset{(-)}{\frac{\partial L_i^D}{\partial R^L}}
\end{pmatrix} \\
&= \begin{pmatrix}
-1 & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & 0 \\
0 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & 0 \\
0 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & \overset{(-)}{F_{34}} \\
0 & 0 & \overset{(-)}{F_{43}} & \overset{(+)}{F_{44}}
\end{pmatrix}
\end{aligned}
$$

Entries in the Jacobian are labeled in the following way: The first subscript denotes the number of the market within the equation system, the second subscript gives the number of the endogenous variable according to following definition: $1 : C^S, 2 : R^B, 3 : R^D, 4 : R^L$. The signs in brackets above the term indicate whether the derivative is larger or smaller than zero. To show $|J| \neq 0$, the system of four simultaneous equations dF_1 to dF_4 is rewritten in matrix notation. On the right-hand side of the equation system, the second subscript explicitly denotes the derivative with respect to the exogenous variable. The total system is given as:

$$
\begin{pmatrix}
-1 & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & 0 \\
0 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & 0 \\
0 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & \overset{(-)}{F_{34}} \\
0 & 0 & \overset{(-)}{F_{43}} & \overset{(+)}{F_{44}}
\end{pmatrix}
\begin{pmatrix} dC^S \\ dR^B \\ dR^D \\ dR^L \end{pmatrix}
$$

$$
= \begin{pmatrix}
\overset{(-)}{F_{1R^C}} dR^C + \overset{(-)}{F_{1\eta}} d\eta + \overset{(-)}{F_{1\phi}} d\phi + \overset{(-)}{F_{1\phi^B}} d\phi^B + \overset{(+)}{F_{1\alpha}} d\alpha \\
\overset{(+)}{F_{2R^C}} dR^C + \overset{(-)}{F_{2\eta}} d\eta + \overset{(+)}{F_{2\alpha}} d\alpha \\
\overset{(+)}{F_{3R^C}} dR^C + \overset{(+)}{F_{3\phi}} d\phi + \overset{(+)}{F_{3\alpha}} d\alpha \\
0
\end{pmatrix}
$$

By analogy with previous proofs, we have to show that the Jacobian of the system is different to zero, i.e. $|J| \neq 0$ with

$$
|J| = (-1)\left[\overset{(+)}{F_{22}}\overset{(+)}{F_{33}}\overset{(+)}{F_{44}} - \overset{(-)}{F_{43}}\overset{(-)}{F_{34}}\overset{(+)}{F_{22}} - \overset{(+)}{F_{44}}\overset{(-)}{F_{32}}\overset{(-)}{F_{23}}\right].
$$

The sign turns negative if we assume that direct effects (F_{ij} with $i = j$) dominate indirect effects (F_{ij} with $i \neq j$), i.e. if

$$
(\overset{(+)}{F_{22}}\overset{(+)}{F_{33}}\overset{(+)}{F_{44}}) > (\overset{(-)}{F_{43}}\overset{(-)}{F_{34}}\overset{(+)}{F_{22}} + \overset{(+)}{F_{44}}\overset{(-)}{F_{32}}\overset{(-)}{F_{23}}).
$$

Hence, the determinant of the Jacobian is different from zero with

$$
|J| = (-1)\left[\overset{(+)}{F_{22}}\overset{(+)}{F_{33}}\overset{(+)}{F_{44}} - \overset{(-)}{F_{43}}\overset{(-)}{F_{34}}\overset{(+)}{F_{22}} - \overset{(+)}{F_{44}}\overset{(-)}{F_{32}}\overset{(-)}{F_{23}}\right] < 0
$$

and the system has an implicit solution. ■

A.5 Proof of Proposition 2

Proof. Effects on CBDC supply, derived using Cramer's rule.

As shown in Appendix A.4 $|J| < 0$ holds and we can apply Cramer's rule. By analogy with previous proofs, we generally assume that direct effects (F_{ij} with $i = j$) dominate indirect effects (F_{ij} with $i \neq j$).

(a)

$$
\begin{aligned}
|J_{1R^C}| &= \begin{vmatrix} \triangle_1 & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & 0 \\ \triangle_2 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & 0 \\ \triangle_3 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & \overset{(-)}{F_{34}} \\ 0 & 0 & \overset{(-)}{F_{43}} & \overset{(+)}{F_{44}} \end{vmatrix} \\
&= \triangle_1 \left(\overset{(+)}{F_{22}} \overset{(+)}{F_{33}} \overset{(+)}{F_{44}} - \overset{(-)}{F_{32}} \overset{(-)}{F_{23}} \overset{(+)}{F_{44}} - \overset{(+)}{F_{22}} \overset{(-)}{F_{34}} \overset{(-)}{F_{43}} \right) + \\
&\quad \triangle_2 \left(\overset{(-)}{F_{32}} \overset{(-)}{F_{13}} \overset{(+)}{F_{44}} - \overset{(-)}{F_{12}} \overset{(+)}{F_{33}} \overset{(+)}{F_{44}} + \overset{(-)}{F_{12}} \overset{(-)}{F_{34}} \overset{(-)}{F_{43}} \right) + \\
&\quad \triangle_3 \left(\overset{(-)}{F_{12}} \overset{(-)}{F_{23}} \overset{(+)}{F_{44}} - \overset{(+)}{F_{22}} \overset{(-)}{F_{13}} \overset{(+)}{F_{44}} \right) < 0 \\
\text{with } \triangle_1 &= \overset{(-)}{F_{1R^C}} > 0, \;\; \triangle_2 = \overset{(+)}{F_{2R^C}} > 0, \, \triangle_3 = \overset{(+)}{F_{3R^C}} > 0 \\
\frac{dC^s}{dR^C} &= \frac{|J_{1R^C}|}{|J|} > 0
\end{aligned}
$$

(b)

$$
\begin{aligned}
|J_{1\phi}| &= \begin{vmatrix} \triangle_1 & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & 0 \\ 0 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & 0 \\ \triangle_3 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & \overset{(-)}{F_{34}} \\ 0 & 0 & \overset{(-)}{F_{43}} & \overset{(+)}{F_{44}} \end{vmatrix} \\
&= \triangle_1 \left(\overset{(+)}{F_{22}} \overset{(+)}{F_{33}} \overset{(+)}{F_{44}} - \overset{(-)}{F_{43}} \overset{(-)}{F_{34}} \overset{(+)}{F_{22}} - \overset{(+)}{F_{44}} \overset{(-)}{F_{32}} \overset{(-)}{F_{23}} \right) + \\
&\quad \triangle_3 \left(\overset{(-)}{F_{12}} \overset{(-)}{F_{23}} \overset{(+)}{F_{44}} - \overset{(+)}{F_{44}} \overset{(+)}{F_{22}} \overset{(-)}{F_{13}} \right) \\
\text{with } \triangle_1 &= \overset{(-)}{F_{1\phi}} < 0; \; \triangle_3 = \overset{(+)}{F_{3\phi}} > 0 \\
\frac{dC^s}{d\phi} &= \frac{|J_{1\phi}|}{|J|} \gtreqless 0
\end{aligned}
$$

Given $|J| < 0$, the effect depends on the dominating market.

If the CBDC market reaction ($\triangle_1 < 0$) dominates the deposit market reaction: $|J_{1\phi}| < 0$ and $\frac{dC^s}{d\phi} = \frac{|J_{1\phi}|}{|J|} > 0$.

If the deposit market reaction ($\triangle_3 > 0$) dominates the CBDC market reaction: $|J_{1\phi}| > 0$ and $\frac{dC^s}{d\phi} = \frac{|J_{1\phi}|}{|J|} < 0$.

(c)

$$
\begin{aligned}
\left|J_{1\phi^B}\right| &= \begin{vmatrix} \triangle & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & 0 \\ 0 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & 0 \\ 0 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & \overset{(-)}{F_{34}} \\ 0 & 0 & \overset{(-)}{F_{43}} & \overset{(+)}{F_{44}} \end{vmatrix} \\
&= \triangle \left(\overset{(+)}{F_{22}} \overset{(+)}{F_{33}} \overset{(+)}{F_{44}} - \overset{(-)}{F_{43}} \overset{(-)}{F_{34}} \overset{(+)}{F_{22}} - \overset{(+)}{F_{44}} \overset{(-)}{F_{32}} \overset{(-)}{F_{23}} \right) < 0 \\
\text{with } \triangle &= \overset{(-)}{F_{1\phi^B}} < 0 \\
\frac{dC^s}{d\phi^B} &= \frac{\left|J_{1\phi^B}\right|}{|J|} > 0.
\end{aligned}
$$

■

A.6 Proof of Proposition 3

Proof. Effects on the deposit rate, derived using Cramer's rule.

As shown in Appendix A.4 $|J| < 0$ holds and we can apply Cramer's rule. By analogy with previous proofs, we generally assume that direct effects (F_{ij} with $i = j$) dominate indirect effects (F_{ij} with $i \neq j$).

(a)

$$
\begin{aligned}
|J_{3R^C}| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \triangle_1 & 0 \\ 0 & \overset{(+)}{F_{22}} & \triangle_2 & 0 \\ 0 & \overset{(-)}{F_{32}} & \triangle_3 & \overset{(-)}{F_{34}} \\ 0 & 0 & 0 & \overset{(+)}{F_{44}} \end{vmatrix} \\
&= (-1)\left(\overset{(+)}{F_{22}}\triangle_3\overset{(+)}{F_{44}} - \overset{(+)}{F_{44}}\overset{(-)}{F_{32}}\triangle_2\right) \\
&= \triangle_2\overset{(+)}{F_{44}}\overset{(-)}{F_{32}} - \triangle_3\overset{(+)}{F_{22}}\overset{(+)}{F_{44}} < 0 \\
\text{with } \triangle_2 &= \overset{(+)}{F_{2R^C}} > 0,\ \triangle_3 = \overset{(+)}{F_{3R^C}} > 0 \\
\frac{dR^D}{dR^C} &= \frac{|J_{3R^C}|}{|J|} > 0
\end{aligned}
$$

(b)

$$
\begin{aligned}
|J_{3\phi}| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \triangle_1 & 0 \\ 0 & \overset{(+)}{F_{22}} & 0 & 0 \\ 0 & \overset{(-)}{F_{32}} & \triangle_3 & \overset{(-)}{F_{34}} \\ 0 & 0 & 0 & \overset{(+)}{F_{44}} \end{vmatrix} \\
&= (-1)\left(\overset{(+)}{F_{22}}\triangle_3\overset{(+)}{F_{44}}\right) < 0 \\
\text{with } \triangle_3 &= \overset{(+)}{F_{3\phi}} > 0 \\
\frac{dR^D}{d\phi} &= \frac{|J_{3\phi}|}{|J|} > 0
\end{aligned}
$$

(c)

$$
\begin{aligned}
\left|J_{3\phi^B}\right| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \triangle & 0 \\ 0 & \overset{(+)}{F_{22}} & 0 & 0 \\ 0 & \overset{(-)}{F_{32}} & 0 & \overset{(-)}{F_{34}} \\ 0 & 0 & 0 & \overset{(+)}{F_{44}} \end{vmatrix} = 0 \\
\frac{dR^D}{d\phi^B} &= \frac{|J_{3\phi^B}|}{|J|} = 0
\end{aligned}
$$

■

A.7 Proof of Proposition 4

Proof. Effects on the credit rate, derived using Cramer's rule.

As shown in Appendix A.4 $|J| < 0$ holds and we can apply Cramer's rule. By analogy with previous proofs, we generally assume that direct effects (F_{ij} with $i = j$) dominate indirect effects (F_{ij} with $i \neq j$).

(a)

$$
\begin{aligned}
|J_{4R^C}| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & \triangle_1 \\ 0 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & \triangle_2 \\ 0 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & \triangle_3 \\ 0 & 0 & \overset{(-)}{F_{43}} & 0 \end{vmatrix} \\
&= -\triangle_2 \overset{(-)}{F_{32}} \overset{(-)}{F_{43}} + \triangle_3 \overset{(-)}{F_{43}} \overset{(+)}{F_{22}} < 0 \\
\text{with } \triangle_2 &= \overset{(+)}{F_{2R^C}} > 0, \triangle_3 = \overset{(+)}{F_{3R^C}} > 0 \\
\frac{dR^L}{dR^C} &= \frac{|J_{4R^C}|}{|J|} > 0
\end{aligned}
$$

(b)

$$
\begin{aligned}
|J_{4\phi}| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & \triangle_1 \\ 0 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & 0 \\ 0 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & \triangle_3 \\ 0 & 0 & \overset{(-)}{F_{43}} & 0 \end{vmatrix} \\
&= \triangle_3 \overset{(-)}{F_{43}} \overset{(+)}{F_{22}} < 0 \\
\text{with } \triangle_3 &= \overset{(+)}{F_{3\phi}} > 0 \\
\frac{dR^L}{d\phi} &= \frac{|J_{4\phi}|}{|J|} > 0
\end{aligned}
$$

(c)

$$
\begin{aligned}
\left|J_{4\phi^B}\right| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & \triangle \\ 0 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & 0 \\ 0 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & 0 \\ 0 & 0 & \overset{(-)}{F_{43}} & 0 \end{vmatrix} = 0 \\
\frac{dR^L}{d\phi^B} &= \frac{|J_{4\phi^B}|}{|J|} = 0
\end{aligned}
$$

■

A.8 Proof of Proposition 5

Proof. Effects on the bond rate, derived using Cramer's rule.

As shown in Appendix A.4 $|J| < 0$ holds and we can apply Cramer's rule. By analogy with previous proofs, we generally assume that direct effects (F_{ij} with $i = j$) dominate indirect effects (F_{ij} with $i \neq j$).

(a)

$$
\begin{aligned}
|J_{2R^C}| &= \begin{vmatrix} -1 & \triangle_1 & \overset{(-)}{F_{13}} & 0 \\ 0 & \triangle_2 & \overset{(-)}{F_{23}} & 0 \\ 0 & \triangle_3 & \overset{(+)}{F_{33}} & \overset{(-)}{F_{34}} \\ 0 & 0 & \overset{(-)}{F_{43}} & \overset{(+)}{F_{44}} \end{vmatrix} \\
&= \triangle_2 \overset{(-)}{F_{43}} \overset{(-)}{F_{34}} - \triangle_2 \overset{(+)}{F_{33}} \overset{(+)}{F_{44}} + \triangle_3 \overset{(+)}{F_{44}} \overset{(-)}{F_{23}} < 0 \\
\text{with } \triangle_2 &= \overset{(+)}{F_{2R^C}} > 0, \triangle_3 = \overset{(+)}{F_{3R^C}} > 0 \\
\frac{dR^B}{dR^C} &= \frac{|J_{2R^C}|}{|J|} > 0
\end{aligned}
$$

(b)

$$
\begin{aligned}
|J_{2\phi}| &= \begin{vmatrix} -1 & \triangle_1 & \overset{(-)}{F_{13}} & 0 \\ 0 & 0 & \overset{(-)}{F_{23}} & 0 \\ 0 & \triangle_3 & \overset{(+)}{F_{33}} & \overset{(-)}{F_{34}} \\ 0 & 0 & \overset{(-)}{F_{43}} & \overset{(+)}{F_{44}} \end{vmatrix} \\
&= \triangle_3 \overset{(+)}{F_{44}} \overset{(-)}{F_{23}} < 0 \\
\text{with } \triangle_3 &= \overset{(+)}{F_{3\phi}} > 0 \\
\frac{dR^B}{d\phi} &= \frac{|J_{2\phi}|}{|J|} > 0
\end{aligned}
$$

(c)

$$
\begin{aligned}
\left|J_{2\phi^B}\right| &= \begin{vmatrix} -1 & \triangle & \overset{(-)}{F_{13}} & 0 \\ 0 & 0 & \overset{(-)}{F_{23}} & 0 \\ 0 & 0 & \overset{(+)}{F_{33}} & \overset{(-)}{F_{34}} \\ 0 & 0 & \overset{(-)}{F_{43}} & \overset{(+)}{F_{44}} \end{vmatrix} = 0 \\
\frac{dR^B}{d\phi^B} &= \frac{|J_{2\phi^B}|}{|J|} = 0
\end{aligned}
$$

■

A.9 Proof of Proposition 6

Proof. Effects of the run-off rate, derived using Cramer's rule.

As shown in Appendix A.4 $|J| < 0$ holds and we can apply Cramer's rule.

(a)

$$\begin{aligned}
|J_{3\alpha}| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \triangle_1 & 0 \\ 0 & \overset{(+)}{F_{22}} & \triangle_2 & 0 \\ 0 & \overset{(-)}{F_{32}} & \triangle_3 & \overset{(-)}{F_{34}} \\ 0 & 0 & 0 & \overset{(+)}{F_{44}} \end{vmatrix} \\
&= (-1)\left(\overset{(+)}{F_{22}}\overset{(+)}{F_{44}}\triangle_3 - \overset{(+)}{F_{44}}\overset{(-)}{F_{32}}\triangle_2\right) < 0 \\
\text{with } \triangle_2 &= \overset{(+)}{F_{2\alpha}} > 0, \triangle_3 = \overset{(+)}{F_{3\alpha}} > 0 \\
\frac{dR^D}{d\alpha} &= \frac{|J_{3\alpha}|}{|J|} > 0
\end{aligned}$$

(b)

$$\begin{aligned}
|J_{4\alpha}| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & \triangle_1 \\ 0 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & \triangle_2 \\ 0 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & \triangle_3 \\ 0 & 0 & \overset{(-)}{F_{43}} & 0 \end{vmatrix} \\
&= (-1)\left(\overset{(-)}{F_{32}}\overset{(-)}{F_{43}}\triangle_2 - \overset{(-)}{F_{43}}\overset{(+)}{F_{22}}\triangle_3\right) < 0 \\
\text{with } \overset{(+)}{F_{2\alpha}} &> 0, \triangle_3 = \overset{(+)}{F_{3\alpha}} > 0 \\
\frac{dR^L}{d\alpha} &= \frac{|J_{4\alpha}|}{|J|} > 0
\end{aligned}$$

■

A.10 Proof of Proposition 7

Proof. Effects of the efficiency in HQLA portfolio management, derived using Cramer's rule.

As shown in Appendix A.4 $|J| < 0$ holds and we can apply Cramer's rule.

(a)

$$\begin{aligned}
|J_{3\eta}| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \triangle_1 & 0 \\ 0 & \overset{(+)}{F_{22}} & \triangle_2 & 0 \\ 0 & \overset{(-)}{F_{32}} & 0 & \overset{(-)}{F_{34}} \\ 0 & 0 & 0 & \overset{(+)}{F_{44}} \end{vmatrix} \\
&= \overset{(+)}{F_{44}}\overset{(-)}{F_{32}}\triangle_2 > 0 \\
\text{with } \triangle &= \overset{(-)}{F_{2\eta}} < 0 \\
\frac{dR^D}{d\eta} &= \frac{|J_{3\eta}|}{|J|} < 0
\end{aligned}$$

(b)

$$\begin{aligned}
|J_{4\eta}| &= \begin{vmatrix} -1 & \overset{(-)}{F_{12}} & \overset{(-)}{F_{13}} & \triangle_1 \\ 0 & \overset{(+)}{F_{22}} & \overset{(-)}{F_{23}} & \triangle_2 \\ 0 & \overset{(-)}{F_{32}} & \overset{(+)}{F_{33}} & 0 \\ 0 & 0 & \overset{(-)}{F_{43}} & 0 \end{vmatrix} \\
&= -\triangle_2\overset{(-)}{F_{32}}\overset{(-)}{F_{43}} > 0 \\
\text{with } \triangle_2 &= \overset{(-)}{F_{2\eta}} < 0 \\
\frac{dR^L}{d\eta} &= \frac{|J_{4\eta}|}{|J|} < 0
\end{aligned}$$

■