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Central bank digital currency and monetary policy implementation

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Abstract

This paper discusses the impact that a retail central bank digital currency (CBDC) could have on the implementation of monetary policy. Monetary policy implementation could be affected if the introduction of the retail CBDC changes the volume of commercial bank deposits held by customers, which would, in turn, affect central bank reserves. While it is often assumed that customer deposits would decrease if a CBDC was introduced, we provide arguments why this is by no means clear cut and deposits could even increase. If bank deposits do decrease, banks would need to draw on, and therefore reduce, their central bank reserve holdings. Moreover, uncertainty as to the timing and extent of any conversions of deposits into CBDC might prompt banks to scale up their demand for central bank reserves in order to hold larger precautionary buffers. Consequently, central banks might need to adjust their reserve supply and other features of their monetary policy implementation, depending, for example, on whether they use a floor or a corridor system for monetary policy implementation. In the specific case of the digital euro, the features already envisaged for its design would make it possible to minimise the risk of negative consequences for monetary policy implementation.

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Keywords: Monetary policy implementation, central bank digital currency, central bank reserves.

Non-technical summary

Central banks around the world have been assessing the advantages and disadvantages of CBDCs. A CBDC is a new form of central bank money. Like banknotes, it is a claim on the issuing central bank that can be used to make payments with instant settlement 24 hours a day, seven days a week. But unlike banknotes, it exists only in digital form. If it is available to the general public, including households and non-financial corporations, it is referred to as a retail CBDC. If it can only be used by (financial) institutions, it is referred to as a wholesale CBDC. In 2022, 80 out of the 86 central banks that responded to a survey conducted by the Bank for International Settlement (BIS) said that they were engaged in work on the issue of CBDCs.[1] A small number of central banks had already introduced a retail CBDC (the central banks of Nigeria, the Bahamas, Jamaica and the Eastern Caribbean Currency Union) or were conducting pilot tests (China, India). Other central banks have announced concrete investigations into a retail CBDC (e.g. the Bank of England and the ECB).

In this paper, we discuss the potential implications of a retail CBDC for the implementation of monetary policy. One of the main objectives of monetary policy implementation is to steer short-term market interest rates to the level that is considered appropriate for the monetary policy being pursued. For most central banks, this is achieved by, among other things, controlling the amount of reserves that the banking sector holds with the central bank. Given that a retail CBDC could have an impact on the stock of reserves, it is an important factor to be considered in relation to monetary policy implementation.

This paper looks at different aspects of the introduction of a retail CBDC and the likely implications for monetary policy implementation, focusing in particular on the impact on bank deposits and reserves. Its findings can be summarised as follows:

1. Introducing a retail CBDC might change the amounts customers hold on deposit with the commercial banking sector. It is often assumed, or claimed, that a retail CBDC would reduce commercial bank deposits given that customers might convert some of their deposits into CBDC. However, the situation is, we would argue, more subtle and under certain conditions bank deposits might even increase, in particular if the CBDC is designed so that conversion of bank deposits into and out of CBDC was a highly convenient option. In a banking crisis, however, a CBDC could result in a significant loss of bank deposits. To avoid this, a limit on the amount in CBDC any individual user could hold is likely to be a critical feature. This is discussed in detail in Section 2.
2. The impact of a retail CBDC on bank deposits might also depend on whether or not the CBDC is remunerated. Most CBDC that have been

[1] See Kosse and Mattei (2023) for more information on the results of the BIS survey.

launched or are being developed are unremunerated (see Box 2), which could, theoretically, have a strong negative impact on bank deposits if market interest rates were to move into negative territory and this was reflected in the rates offered on bank deposits. Were this to be the case, an unremunerated CBDC could make banks reluctant to apply negative rates on bank deposits, weakening the transmission of negative central bank policy rates. This may strengthen the argument for a CBDC holding limit. Empirical findings for the euro area suggest, however, that the impact might, in fact, be relatively moderate even without a holding limit, given that interest rates on household overnight bank deposits barely slipped below zero when market interest rates turned negative in the euro area. The situation was to some extent different for bank deposits by corporations. This is discussed in Box 1.

3. If a CBDC were to result in a reduction in bank deposits and the central bank did not lengthen its balance sheet, then the reserves the banking sector holds with the central bank might decline. Replacing the deposits lost with market funding would not help to restore those reserves; only additional liquidity provided by the central bank could serve this purpose. This is discussed in Section 3.1.
4. A CBDC might create challenges for monetary policy implementation if it were to lead to a significant lengthening of the central bank balance sheet. For assessing the amount of CBDC that could be put into circulation, central banks would need to take into account both the minimum amount of reserves required for the smooth implementation of monetary policy and the maximum amount of additional liquidity that they are prepared to provide (see Section 3.2). Clearly, these are just some of the aspects, among many others, that would need to be considered in assessing the amount of CBDC that could be put into circulation.
5. If monetary policy is implemented in a floor system (see Section 4.1 and Box 3), the introduction of a CBDC (i) may require additional central bank asset purchases or additional central bank credit offered at sufficiently favourable conditions and (ii) may increase the minimum amount of reserves required for a smooth monetary policy implementation. This is because the introduction of a CBDC might prompt banks to hold larger amounts of reserves as buffers to address potentially large (on aggregate) client requests to convert deposits into CBDC.
6. If monetary policy is implemented in a corridor system (see Section 4.2 and Box 4), the central bank could consider different strategies to respond to the introduction of a CBDC, such as more frequent monetary policy operations (including fine-tuning operations), a narrower central bank interest rate corridor or higher minimum reserve requirements.

The current paper considers a generic retail CBDC but, when relevant, also discusses how the design features envisaged for a digital euro would make it possible to address the risk of negative consequences for monetary policy implementation. In October 2021 the ECB started a two-year investigation into the possibility of issuing a CBDC for the euro area: the digital euro. In October 2023 the ECB decided to launch a preparation phase as a next step and published a report summarising the design features envisaged for a digital euro.[2] Having examined those features, the current paper concludes that they would reduce the risk of a digital euro having negative consequences for monetary policy implementation.

2 See ECB (2023b).

1 Introduction

Central banks around the world have been assessing the advantages and disadvantages of CBDCs. A CBDC is a new form of central bank money. Like banknotes, it is a claim on the issuing central bank that can be used to make payments with instant settlement around the clock. But unlike banknotes, it exists only in digital form. If it is available to the general public, including households and non-financial corporations, it is referred to as a retail CBDC. If it can be used only by (financial) institutions, it is referred to as a wholesale CBDC.[3] In 2022, 80 out of the 86 central banks that responded to a survey conducted by the BIS said that they were engaged in work on the issue of CBDCs.[4] A small number of central banks have already introduced a retail CBDC (the central banks of Nigeria, the Bahamas, Jamaica and the Eastern Caribbean Currency Union) or are conducting pilot tests (China, India). Other central banks have announced very concrete investigations into a retail CBDC (e.g. the Bank of England and the ECB).[5]

In this paper, we discuss the potential implications of a retail CBDC for the implementation of monetary policy. One of the main objectives of monetary policy implementation is to steer short-term market interest rates to the level that is considered appropriate for the monetary policy being pursued. For most central banks, this is achieved by, among other things, controlling the amount of reserves that the banking sector holds with the central bank. Given that a retail CBDC could have an impact on the amount of reserves, it is an important factor to be considered in relation to monetary policy implementation.

The rest of this paper is organised into four sections and four boxes. Section 2 and Box 1 discuss the impact of a retail CBDC on the deposits held by customers with commercial banks, given that this affects the amount of central bank reserves and therefore monetary policy implementation. Section 3 first analyses how a retail CBDC might influence the aggregate balance sheets of the central bank, the banking sector and the non-bank sector. It then discusses the amount of bank deposits a central bank could allow customers to convert into CBDC given some of the constraints arising from the aggregate balance sheets. Box 2 provides an overview of the current CBDC initiatives of central banks worldwide. Section 4, together with Boxes 3 and 4, provides a detailed assessment, including a model-based analysis, of the consequences that a CBDC might have on the way that central banks could implement monetary policy, distinguishing between floor-based

3 For a detailed discussion of the definition of a CBDC and its core design features, see, for example, Section 2 and 3 of Meaning et al (2021).

4 See Kosse and Mattei (2023) for more information on the results of the BIS survey.

5 See Box 2 for more information.

and corridor-based monetary policy implementation systems. Section 5 concludes.

2 Impact of a CBDC on the demand for bank deposits

In this section, we discuss the impact that the introduction of a CBDC might have on the demand for bank deposits. We show that the impact is, ex ante, ambiguous, given that several of the CBDC's inherent features as well as design choices interact with each other in ways that can offset their effect on the demand for deposits.[6]

Following the introduction of a CBDC, some of the goods and services that were previously paid for with cash (banknotes and coins) or through bank deposits will be paid for with CBDC. Currently there are, broadly speaking, two types of means of payment: bank deposits and cash.[7] A CBDC would be a third means of payment. While the introduction of a CBDC would have relatively little impact on the types and quantities of the goods and services people will want to buy, it may have a strong impact on how people pay for those goods and services: some items that would have been paid for with cash or from bank deposits would be settled in CBDC.

If individuals wished to pay for an item with a CBDC, they might need to convert cash or bank deposits into CBDC beforehand. This would generate a demand for CBDC and reduce the demand for cash and/or bank deposits. However, the mechanics of converting bank deposits into other means of payment would have a decisive impact on demand for bank deposits. To give a simple example,[8] an individual initially holds only bank deposits and would like to conduct transactions for an amount P on each of two consecutive days. Assuming that a CBDC is not available, that individual wishes to make a cash payment of C and a payment from a bank deposit of D $(C + D = P)$ on each of the days. The split of P into C and D is assumed to be driven by the acceptability of the respective forms of payment for the transactions to be made. Since going to an ATM on two separate days would be inconvenient, the individual decides to go there only on day 1 and to withdraw $2 \cdot C$ in cash. Consequently, the individual pays one cash amount of C on day 1 and holds the other cash amount of C overnight from day 1 to day 2. Assuming that amounts paid to merchants in central bank money (cash or, in the further course of our example, CBDC) are converted into bank deposits on the same day, i.e. the sums are not held by them in cash overnight, C is the portion of the cash withdrawn from the individual's deposits that remains in circulation from day 1 to day 2.

6 Papers that try to estimate the demand for CBDC, implying an estimate of the impact of a CBDC on the demand for bank deposits, include for example Li (2023) and Gross and Letizia (2023). To our knowledge, our paper is the first to conclude that a CBDC might possibly have a positive impact on the demand for bank deposits.

7 For the purposes of this illustration, we have disregard other means of payment, such as credit cards or e-money.

8 The example is loosely inspired by Baumol (1952).

This situation is summarised in the first column of Table 1. However, holding cash overnight exposes individuals to physical security risks. Consequently, in cases where both cash and bank deposit transfers are accepted for payment, the individual may prefer to pay through a bank deposit so that the amount of cash withdrawn can be kept as small as possible.

Table 1

Holding of cash, deposits and CBDC

			Without a CBDC	Inconvenient CBDC conversion	Convenient CBDC conversion
Day 1	**Withdrawals**	**Cash**	2C	2C*	2C*
		CBDC	-	2Z*	Z*
	Payments	**Cash**	C	C*	C*
		Deposits	D	D*	D*
		CBDC	-	Z*	Z*
	End of day Balances	**Cash**	C	C*	C*
		CBDC	-	Z*	-
Day 2	**Withdrawals**	**Cash**	-	-	-
		CBDC	-	-	Z*
	Payments	**Cash**	C	C*	C*
		Deposits	D	D*	D*
		CBDC	-	Z*	Z*

The ability to pay using CBDC may incentivise people to hold a significant amount of their funds in this form and hold less in bank deposits. Taking the above example, suppose that a CBDC has been introduced and is accepted for settling transactions, some of which were previously made in cash and some through bank deposits. The individual would now like to make, on each of the two days, a cash payment of C^*, a payment through bank deposits of D^* and a CBDC payment of Z^*, where $C^* + D^* + Z^* = C + D = P$. On day 1, she now withdraws a cash amount of $2 \cdot C^*$ and converts an amount of $2 \cdot Z^*$ of deposits into CBDC, assuming that it is also sufficiently inconvenient to convert bank deposits into CBDC on each of the two days. As a result, she now holds an amount of central bank money (cash plus CBDC) of $C^* + Z^*$ overnight from day 1 to day 2. In contrast to cash, CBDC is not subject to physical security risks and might therefore become the payment option of choice once a digital currency is introduced. This could lead to less demand for bank deposits, i.e. $C^* + Z^* > C$ and $D^* < D,$ if a CBDC is introduced. A situation in which there is a CBDC but converting bank deposits into CBDC is not straightforward is summarised in the second column of Table 1.

If, however, customers find converting bank deposits into and out of CBDC straightforward and a convenient option, then the introduction of a CBDC might increase the demand for bank deposits. Again taking the example set out above but now assuming that the CBDC has been designed so that converting bank deposits into CBDC is straightforward – meaning that the conversion is instantaneous, possible at all times, costless and easy – the situation would be as follows. The individual now decides to convert only a single amount of Z^* into CBDC on day 1 and the same amount again on day 2. This is particularly likely if bank deposits are better remunerated than CBDC. As a result, the individual holds a cash amount of C^* overnight, but no CBDC and, given that $C^* < C,$ the amount held in the individual's bank deposits overnight has now increased as compared with the situation in which no CBDC exists. This is illustrated in the third column of Table 1.

CBDC design features, such as a waterfall and reverse waterfall mechanism, that allow the automatic conversion of bank deposits into and out of CBDC would have a significant impact in terms of convenience and are therefore particularly relevant for reducing incentives to accumulate CBDC rather than bank deposits. A waterfall is a mechanism whereby if CBDC holdings exceed a prespecified threshold, e.g. because of a large incoming payment, the excess amount is automatically and immediately transferred into the payee's bank account, i.e. converted into a bank deposit. A reverse waterfall allows a payer to make a CBDC payment that is larger than the payer's CBDC holdings: any amount needed for the payment and not available in the payer's CBDC account would be automatically transferred from the payer's bank account into the CBDC account and payment is then triggered instantly. It should be noted that the reverse waterfall can be seen as a tool that would make the conversion of bank deposits into CBDC a very convenient option. An individual might decide not to have any CBDC holdings at all but could nevertheless make CBDC payments given that the reverse waterfall mechanism would always convert any required amount from bank deposits into CBDC as and when needed. Consequently, a CBDC with a reverse waterfall could increase the demand for bank deposits.

Widespread adoption of CBDC as a payment instrument would not necessarily result in reduced demand for bank deposits. Payment technologies are network technologies. If many people decide to use a technology, many more will follow.[9] However, this does not necessarily mean that extensive adoption of CBDC as a payment instrument would reduce demand for bank deposits. As indicated above, how straightforward it is to convert into and out of CBDC could be expected to be an important driver of adoption, together with general acceptance among merchants of payments in CBDC and the creation of a symbiotic ecosystem alongside other means of payment.

[9] For a model-based discussion of the network effects of a CBDC, see, for example, Agur et al (2022).

While the arguments above focus on the payment function, a CBDC could, in principle, also be used as a store of value. The extent to which a CBDC might be used as a store of value is likely to depend primarily on its remuneration, discussed in Box 1, and the perceived risk of holding alternative stores of value, such as bank deposits.

With regard to the interaction of CBDC holdings and the perceived risk of holding bank deposits, the impact of CBDC on the demand for deposits is likely to be highly situation-specific. CBDC is a liability of the central bank in its domestic currency and, as such, is not subject to default risk. This could make it a particularly attractive option in a banking crisis, when depositors may wish to convert large amounts of bank deposits into central bank money for fear of losses. Converting bank deposits into CBDC would be easier and faster than converting them into banknotes. Furthermore, holding CBDC would not be subject to the risks, storage and insurance costs that holding large amounts of cash entails.[10] As such, a CBDC might reduce the demand for bank deposits in a banking crisis.[11] However, holding limits might be a tool for preventing large holdings of CBDC to the detriment of bank deposits in such a situation (and more generally), i.e. they might limit the possible negative impact of a CBDC on the demand for bank deposits.[12]

The ECB has announced its intention to offer waterfall and reverse waterfall functionalities to all digital euro end-users and to apply digital euro holding limits.[13] The arguments set out above suggest that by incorporating these design features, the digital euro might not have a negative impact on the demand for bank deposits in normal times and could avoid undue loss of bank deposits during a banking crisis.

Given that a CBDC which reduces the demand for bank deposits may be challenging for monetary policy implementation, we focus on this issue in the following sections. As argued in this section, a CBDC could increase or reduce the demand for bank deposits, depending on the features incorporated into it. If a CBDC were to reduce the demand for bank deposits, the banking sector may lose an important funding source. This could be challenging for monetary policy implementation. We therefore analyse the case of a CBDC that reduces the demand for bank deposits in the sections below with a view to motivating design features that could prevent any such reduction.

10 Rather than converting bank deposits into CBDC in a banking crisis, depositors could consider moving deposits away from banks that are perceived to be risky to banks that are perceived as being save. However, where people have only one bank account plus a CBDC wallet that they use for payment purposes, moving deposits to another bank would then require a second account to be opened with a commercial bank. Moving funds into CBDC would then be easier and faster.

11 While a CBDC may increase the loss of bank deposits in a banking crisis, it could well make banking crises less likely. See, for example, Keister and Monnet (2022) who argue that a CBDC could change the behaviour of banks and the strategy pursued by regulators thereby decreasing financial fragility.

12 See Bindseil et. al. (2024) for a related discussion.

13 See ECB (2023b).

Box 1
The impact of a zero remuneration of CBDC on the demand for bank deposits[14]

The impact of a CBDC on the demand for bank deposits would depend significantly on the levels of remuneration of these two instruments. If the CBDC benefited from higher remuneration than bank deposits, people might prefer to hold more CBDC and hold less in bank deposits, regardless of whether or not they use the CBDC for payment purposes. In order to limit any loss of deposits in such circumstances, banks might react by increasing the remuneration paid on bank deposits. This strategy might, however, be seen by the banks as being less profitable, depending, for example, on the amount of reserves available to the banking sector, in which case they might prefer to accept the loss of deposits.

In order to avoid any remuneration of CBDC influencing the demand for bank deposits, central banks could consider various strategies. They could, for example, offer CBDC remuneration at the level of the (average) remuneration on bank deposits (possibly minus a constant spread). This approach might, however, be considered too complicated for a retail CBDC. Furthermore, at times when central bank policy rates are negative, the average remuneration on bank deposits might also slip into negative territory. If the remuneration on CBDC is then also set at a negative level, the reputation and acceptance of CBDC could suffer.

Zero remuneration would mirror the remuneration on banknotes and is the approach that most, if not all, central banks consider preferable for a CBDC (see Box 2). At times when rates on bank deposits are high, for example due to high central bank policy rates, zero remuneration of CBDC could result in lower demand for CBDC. When bank deposit rates are negative, for example due to negative central bank policy rates, zero remuneration of CBDC could lead to lower demand for bank deposits. This might make banks reluctant to apply negative rates to bank deposits, weakening the transmission of negative central bank policy rates. However, if a relatively tight CBDC holding limit is applied, the remuneration of CBDC relative to that on bank deposits might have very little impact on the demand for bank deposits. For instance, Eurosystem officials have mentioned a digital euro holding limit for natural persons of €3,000 to € 4,000 as an option.[15] In addition, it is envisaged to apply a zero remuneration to the digital euro.[16] The lowest ECB policy rate was -0.5% (between September 2019 and July 2022). Let us suppose that the average remuneration on bank deposits falls to this level. Zero remuneration of a digital euro and a holding limit of €3,000 would than mean that the loss that an individual could avoid by converting a bank deposit into digital euro up to the maximum holding limit would be a mere €15 per year.[17]

Even without tight holding limits, zero remuneration of CBDC holdings by households might have limited impact on their level of demand for bank deposits given that the remuneration on household overnight bank deposits tends to

[14] For related discussions, see, for example, Section 3.2 in Meaning et al (2021) and Section 2.1 in Adalid et al (2022).

[15] See Panetta (2022).

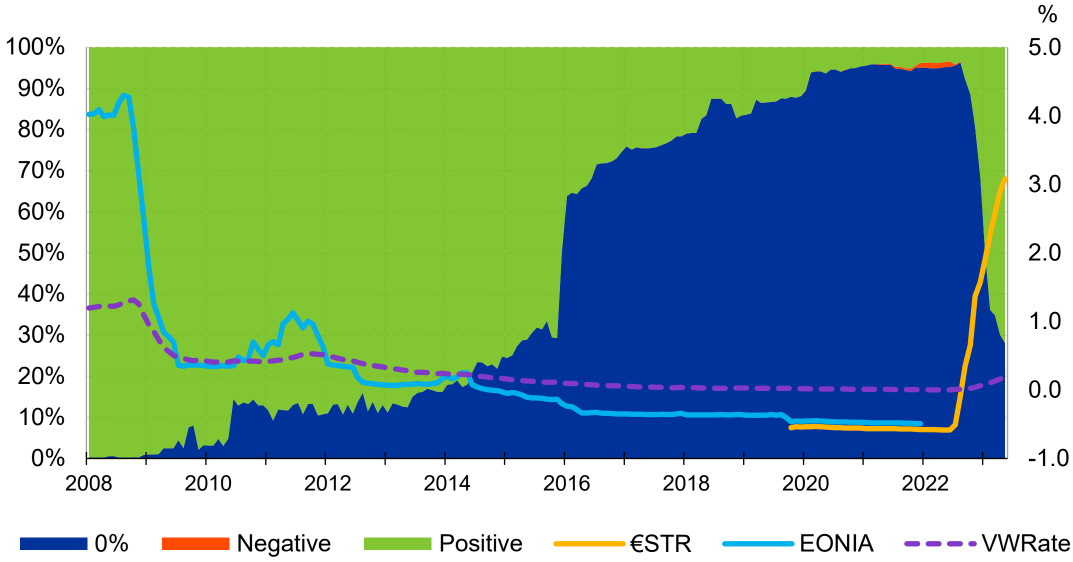
[16] See ECB (2023b).

[17] As an alternative to a CBDC holding limit, Bindseil (2020) discusses a tiered system of CBDC remuneration, i.e. the interest would be lower for CBDC holdings above a given ceiling.

deviate relatively little from zero. The implications of zero remuneration of CBDC holdings on the demand for deposits might differ for households and for corporations. Starting with households and taking the euro area as an example, Chart 1 shows that average interest rates on overnight bank deposits of households barely slipped into negative territory during the period when market interest rates in the euro area were negative but instead stayed close to zero. Zero remuneration of CBDC at that time would not have provided a sufficient incentive for households to convert bank deposits into CBDC. And, when policy rates and money market interest rates were relatively high, at around 4%, in 2008, the average rates on overnight bank deposits barely exceeded 1%, again providing little incentive for households to convert significant amounts of CBDC into bank deposits even if CBDC had been remunerated at 0%.[18] However, the stickiness of interest rates on bank deposits at 0% when central bank policy rates and market interest rates turn negative may be undesirable from a monetary policy perspective given that it means limited transmission of policy rates. And zero CBDC remuneration without a relatively tight CBDC holding limit could cement this stickiness and result in a "reversal interest rate", i.e. a policy rate level below which further rate cuts would tend to have a tightening rather than loosening effects on the economy, thereby curtailing monetary policy space.[19]

Chart 1

Remuneration of overnight bank deposits held by households



Source: Individual monetary financial institution interest rate (IMIR) data.
Notes: The blue area is the share of deposits remunerated at rates between -0.05% and 0.05%. The green area is the share of deposits remunerated at rates above 0.05% and the red area is the share of deposits remunerated at rates below -0.05%. €STR denotes the euro short-term rate. EONIA denotes the interbank overnight lending reference rate for the euro that was discontinued on 3 January 2022 and replaced with the €STR. VWRate denotes the volume weighted rate on overnight bank deposits.

In the absence of any CBDC holding limits, zero remuneration of the CBDC holdings of non-financial corporations might have a stronger impact on the demand for bank deposits. Chart 2 shows that the remuneration of overnight bank

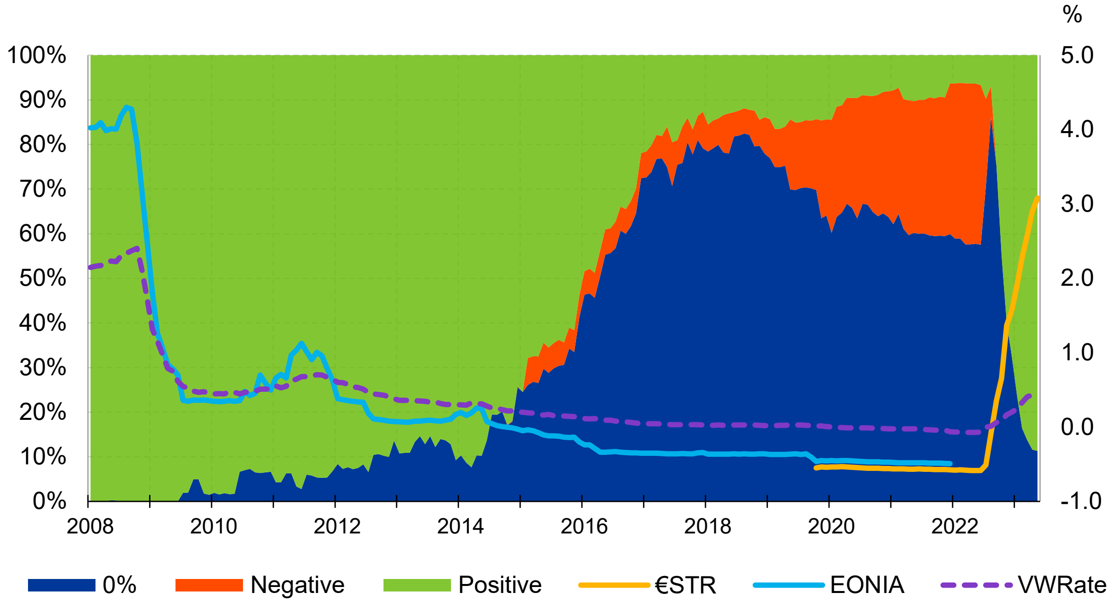
18 Other bank deposit products, such as term deposits, tend to offer interest rates that move more closely with money market rates but they are less liquid and therefore are unlikely to be a relevant alternative for funds that are intended to be highly liquid and immediately available for transactions purposes.

19 For more information on the "reversal interest rate" concept, see Abadi et al. (2023).

deposits held by non-financial corporations, i.e. business users, follows market rates, and therefore central bank policy rates, much more closely than the remuneration of household deposits. Zero remuneration of CBDC held by non-financial corporations could lead to them converting large amounts of bank deposits into CBDC if the central bank policy rate, and therefore also interest rates on corporate bank deposits, were to turn negative. For this reason, zero remuneration of CBDC holdings would need, in all likelihood, to be accompanied by a tight CBDC holding limit for such corporations. This could be combined with a waterfall and a reverse waterfall for non-financial corporations (or possibly even for all CBDC users). Waterfalls would make it possible for such corporations to make and receive CBDC payments despite any tight or even zero holding limit.

Chart 2

Remuneration of overnight bank deposits held by non-financial corporations



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Source: Individual monetary financial institution interest rate (IMIR) data.
Notes: The blue area is the share of deposits remunerated at rates between -0.05% and 0.05%. The green area is the share of deposits remunerated at rates above 0.05% and the red area is the share of deposits remunerated at rates below -0.05%. €STR denotes the euro short-term rate. EONIA denotes the interbank overnight lending reference rate for the euro that was discontinued on 3 January 2022 and replaced with the €STR. VWRate denotes the volume weighted rate on overnight bank deposits.

For the digital euro, the ECB plans to apply zero holding limits for business users (corporations)[20] and, as indicated above, holding limits for households of possibly around €3,000 to €4,000, as well as zero remuneration. With these limits, large movements from bank deposits into the digital euro or back as market interest rates change would be avoided, while the waterfall and reverse waterfall functionalities also envisaged for the digital euro would make it possible to receive and make potentially substantial digital euro payments despite the holding limits.

20 See ECB (2023b).

3 The balance sheet mechanics of a CBDC

In this section, we study the impact of a CBDC on the (simplified) balance sheets of three sectors of the economy: the central bank, the aggregate banking sector (excluding the central bank) and the aggregate non-bank sector.[21] We start from the assumption that the introduction of a CBDC would reduce the demand for bank deposits (see Section 2) and study the balance sheet adjustments that would need to take place were this the case. This analysis focuses on the possible reactions to the introduction of a CBDC from the perspective of what is possible given balance sheet constraints. We therefore study what might be called the "balance sheet mechanisms" of a CBDC. Section 4 below provides a detailed analysis of the likely economic behaviour of the banking sector if a CBDC was introduced, the market rates that would emerge from that behaviour and the options open to the central bank in response thereto.

3.1 The impact of a CBDC-induced deposit outflow on reserves

The starting point of this analysis is the (simplified) unconsolidated balance sheets of the three sectors before the introduction of a CBDC. These are given in Chart 3.

The central bank provides credit for monetary policy reasons to the banking sector, the outstanding amount of which is the first item on the asset side of the central bank's balance sheet (CC_0). It also holds a portfolio of financial assets that it has purchased for monetary policy reasons (A_0) together with other assets (COA_0). On the liability side, there are banknotes in circulation (BN_0), reserves of the banking sector held with the central bank (R_0) and other liabilities (COL_0).

The banking sector has the reserves it holds with the central bank (R_0) on the asset side of its balance sheet. The other banking sector asset items are the financial assets owned by the banks and eligible for central bank operations (BE_0) and other assets (BOA_0). We have assumed, for simplicity, that all central bank eligible assets (BE_0) are eligible as collateral in central bank credit operations as well as for the central bank portfolio (i.e. they could be purchased by the central bank for monetary policy reasons). A proportion of the eligible assets is already

[21] Closely related to the analysis in this section are Annex B in BIS (2018), Section 3.1 in Adalid et al (2022), Section 2 in Bindseil (2020) and Malloy et al (2022). Given the focus of this paper, we go somewhat beyond these studies and explicitly consider the amount of unencumbered central bank eligible assets held by banks to be a distinct bank balance sheet item. This item is important for the discussion in Section 3.2.

encumbered as collateral for central bank credit operations or market transactions, while the rest (UBE_0) is in principle available for monetary policy (credit or purchase) operations. On the liability side, the banking sector has bank deposits of customers (D_0), central bank credit (CC_0) and other liabilities (BOL_0).

The non-bank sector includes all households, non-bank corporations and state entities (excluding state-owned banks). On the asset side of its balance sheet, there are banknotes (BN_0), bank deposits (D_0), financial assets eligible for central bank operations (NE_0) and other assets (NOA_0). Non-banks cannot obtain credit from the central bank but could sell central bank eligible assets to the central bank, if the central bank decides to purchase them. For simplicity, we have assumed that the eligible assets held by non-banks are all unencumbered (i.e. not used as collateral in market transactions). The liability side of the non-bank sector balance sheet includes only one item for all liabilities (NOL_0).[22]

Chart 3

Initial balance sheets

Central bank

Assets		Liabilities	
Central bank credit	$\boldsymbol{CC_0}$	Banknotes	$\boldsymbol{BN_0}$
Financial asset portfolio	$\boldsymbol{A_0}$		
Other assets	$\boldsymbol{COA_0}$	Reserves	$\boldsymbol{R_0}$
		Other liabilities	$\boldsymbol{COL_0}$

Banking sector

Assets		Liabilities	
Reserves	$\boldsymbol{R_0}$	Bank deposits	$\boldsymbol{D_0}$
Eligible assets	$\boldsymbol{BE_0}$	Central bank credit	$\boldsymbol{CC_0}$
of which unencumbered	$\boldsymbol{UBE_0}$	Other liabilities	$\boldsymbol{BOL_0}$
Other assets	$\boldsymbol{BOA_0}$		

Non-bank sector

Assets		Liabilities	
Banknotes	$\boldsymbol{BN_0}$	Liabilities	$\boldsymbol{NOL_0}$
Bank deposits	$\boldsymbol{D_0}$		
Eligible assets	$\boldsymbol{NE_0}$		
Other assets	$\boldsymbol{NOA_0}$		

22 The liabilities of the non-bank sector include the equity of the non-banks, credit from banks and bonds issued by non-banks. Credit from banks is an asset of the banking sector (reflected in BE_0 or BOA_0). Bonds issued by non-banks may be held by non-banks (in this case reflected in NE_0 or NOA_0), banks (reflected in BE_0 or BOA_0) or the central bank (A_0 or COA_0).

We have assumed that only non-banks can obtain CBDC. Given that our analysis relates solely to a retail CBDC, banks are excluded from holding CBDC.[23] Non-banks may convert banknotes and bank deposits directly into and out of CBDC. They may not convert other assets (e.g. bonds) directly into CBDC, but would first need to sell them and use the proceeds to purchase CBDC.

If non-banks convert a proportion of their banknotes into CBDC, the banking sector would not be affected. An asset swap would take place on the balance sheet of the non-bank sector: a new asset item, "CBDC", would be shown and banknotes would decrease (to $BN_0 - CBDC_1$). The CBDC is a central bank liability, i.e. the central bank balance sheet would show a liability swap. No other items on the central bank balance sheet would be affected. The banking sector's balance sheet would be completely unaffected (Chart 4).

Chart 4

Conversion by non-banks of banknotes into CBDC

Central bank

Assets		Liabilities	
Central bank credit	CC_0	Banknotes	$BN_0 - CBDC_1$
Financial asset portfolio	A_0	CBDC	$CBDC_1$
Other assets	COA_0	Reserves	R_0
		Other liabilities	COL_0

Banking sector

Assets		Liabilities	
Reserves	R_0	Bank deposits	D_0
Eligible assets	BE_0	Central bank credit	CC_0
of which unencumbered	UBE_0	Other liabilities	BOL_0
Other assets	BOA_0		

Non-bank sector

Assets		Liabilities	
Banknotes	$BN_0 - CBDC_1$	Liabilities	NOL_0
CBDC	$CBDC_1$		
Bank deposits	D_0		
Eligible assets	NE_0		
Other assets	NOA_0		

[23] Some types of non-banks could also be excluded from holding CBDC. For example, there could be a CBDC holding limit of zero for businesses.

If non-banks were to also convert bank deposits into CBDC and the central bank does not lengthen its balance sheet by providing additional liquidity, then the banking sector will lose reserves. An asset swap would take place on the balance sheet of the non-bank sector as the stock of CBDC held by non-banks grew and bank deposits declined (to $D_0 - CBDC_2$). If the central bank does not lengthen its balance sheet, then the reserves held by the banks with the central bank would inevitably decline (to $R_0 - CBDC_2$). This means a liability swap on the balance sheet of the central bank (reserves decline and CBDC increases) and a shortening of the banking sector's balance sheet (bank deposits and reserves decline). These balance sheet mechanics are qualitatively identical to those that occur when non-banks convert their bank deposits into banknotes.

Chart 5

Conversion by non-banks of bank deposits into CBDC; no additional liquidity from the central bank

Central bank

Assets		Liabilities	
Central bank credit	CC_0	Banknotes	$BN_0 - CBDC_1$
Financial asset portfolio	A_0	CBDC	$CBDC_1 + CBDC_2$
Other assets	COA_0	Reserves	$R_0 - CBDC_2$
		Other liabilities	COL_0

Banking sector

Assets		Liabilities	
Reserves	$R_0 - CBDC_2$	Bank deposits	$D_0 - CBDC_2$
Eligible assets	BE_0	Central bank credit	CC_0
of which unencumbered	UBE_0	Other liabilities	BOL_0
Other assets	BOA_0		

Non-bank sector

Assets		Liabilities	
Banknotes	$BN_0 - CBDC_1$	Liabilities	NOL_0
CBDC	$CBDC_1 + CBDC_2$		
Bank deposits	$D_0 - CBDC_2$		
Eligible assets	NE_0		
Other assets	NOA_0		

The banking sector might not be able to avoid a decline of reserves and a corresponding shortening of its balance sheet by replacing

the lost deposits with market funding. It may be argued that the banking sector could replace the lost deposits with market funding (e.g. the issuance of new bonds), thereby avoiding a reduction of reserves and a shortening of the banking sector's balance sheet. This is, however, only possible based on very specific assumptions. For example, if the banking sector were to issues new bonds, these would need to be purchased by non-banks with central bank money: banknotes, CBDC or the deposits of non-banks held with the central bank (which form part of the other liabilities of the central bank (COL_t)). If they were purchased with bank deposits, the funding gap would not close but would be shifted around within the banking sector. This is a very important point to make: if non-banks convert bank deposits into CBDC and the central bank does not lengthen its balance sheet (e.g. by increasing the amount of credit provided or holding a larger financial asset portfolio), then the reserves of the banking sector will have to decline, unless the non-banks were to reduce their claims on the central bank (in the form of banknotes, CBDC or other central bank liabilities). This can clearly be seen from the balance sheet of the central bank.

As the decline in reserves could have unintended implications for the implementation of monetary policy, the central bank might decide to conduct monetary policy operations to re-establish the desired level of reserves. Monetary policy implementation is aimed at steering short-term interbank market rates to a level considered appropriate from a monetary policy perspective. As will be discussed in more detail in Section 4, the amount of reserves is an important factor for the level of the short-term interest rate. If there are ample reserves, short-term interest rates will likely stay close to the rate at which the central bank remunerates (excess) reserves. If reserves are scarce, short-term interest rates will be close to the rate at which the central bank lends out funds. In both cases, if the conversion of bank deposits into CBDC leads to reserves declining below the level required to maintain money market rates in line with the intended monetary policy stance, the central bank can conduct monetary policy operations to provide additional reserves.

The central bank could provide additional credit to the banking sector or purchase more financial assets from the banking sector or from non-banks. Additional central bank credit to the banking sector (CC_3) would lengthen the balance sheets of both the central bank and the banking sector given that the central bank credit provided and the reserves would increase correspondingly (by CC_3). An additional amount of previously unencumbered eligible assets would become encumbered, as collateral for the central bank credit, this amount ($CC_3 + H_3$) being higher than the additional central bank credit provided given that collateral is subject to a haircut (H_3). Additional purchases of financial assets by the central bank from the non-bank sector ($A_{3,N}$) would also lengthen the balance sheets of both the central bank and the banking sector given that the financial assets held by the central bank, bank deposits and reserves would increase (by $A_{3,N}$). Finally, additional purchases of financial assets by the central bank from the banking sector ($A_{3,B}$) would lengthen the central bank's balance sheet and result in an asset swap on the balance sheet of the banking sector with some unencumbered eligible assets being replaced by new reserves. For simplicity, we have assumed throughout that additional central bank credit and additional central bank asset purchases would increase the reserves on a one-to-one basis. We note, however, that this must not always be the case; for example, some of the additional funds provided by the central bank might also increase the other liabilities of the central bank rather than the reserves.

Chart 6

Central bank provision of additional credit and purchase of additional assets from banks and non-banks

Central bank

Assets		Liabilities	
Central bank credit	$CC_0 + CC_3$	Banknotes	$BN_0 - CBDC_1$
Financial asset portfolio	$A_0 + A_{3,N} + A_{3,B}$	CBDC	$CBDC_1 + CBDC_2$
Other assets	COA_0	Reserves	$R_0 - CBDC_2 + CC_3 + A_{3,N} + A_{3,B}$
		Other liabilities	COL_0

Banking sector

Assets		Liabilities	
Reserves	$R_0 - CBDC_2 + CC_3 + A_{3,N} + A_{3,B}$	Bank deposits	$D_0 - CBDC_2 + A_{3,N}$
Eligible assets	$BE_0 - A_{3,B}$	Central bank credit	$CC_0 + CC_3$
of which:		Other liabilities	BOL_0
unencumbered	$UBE_0 - (CC_3 + H_3) - A_{3,B}$		
Other assets	BOA_0		

Non-bank sector

Assets		Liabilities	
Banknotes	$BN_0 - CBDC_1$	Liabilities	NOL_0
CBDC	$CBDC_1 + CBDC_2$		
Bank deposits	$D_0 - CBDC_2 + A_{3,N}$		
Eligible assets	$NE_0 - A_{3,N}$		
Other assets	NOA_0		

3.2 The maximum amount of CBDC-induced deposit outflows tolerable from a monetary policy implementation perspective

Before any CBDC can be introduced, it is necessary to carefully analyse the maximum amount of CBDC-induced deposit losses that would be tolerable from a range of relevant perspectives. A large loss of bank deposits owing to the introduction of a CBDC could have negative consequences for the economy. To avoid this, central banks could use CBDC design features to limit the amount of CBDC in circulation. For example, they could set CBDC holding limits for CBDC users, as indeed envisaged for the digital euro.

The aggregate balance sheet analysis given in Section 3.1 suggests one approach for defining constraints, from a monetary policy implementation perspective, on the amount of deposits that non-banks could be allowed to convert into CBDC. Starting from the balance sheets of Chart 3 above, the central bank could theoretically increase the amount of credit to the banking sector (CC_0) by the maximum amount of additional central bank credit that the banks could collateralise, i.e. by the amount of unencumbered eligible assets (UBE_0) minus collateral haircuts. Furthermore, the central bank could theoretically purchase all central bank eligible assets held by the non-bank sector (NE_0). Assuming that these central bank operations do not affect the amount of banknotes in circulation (BN_0) and other central bank assets (COA_0) and liabilities (COL_0), this would create an additional amount of reserves of $(1-h) \cdot UBE_0 + NE_0$. Here, h denotes the (average) collateral haircut in central bank credit operations. Theoretically, reserves could decline to zero. Given that any (CBDC-induced) loss of bank deposits would lead to a corresponding loss of reserves, the amount of deposit losses (DL) is therefore constrained by

$$(1) \quad DL \leq R_0 + (1-h) \cdot UBE_0 + NE_0.$$

This is a strict constraint that needs to be fulfilled for balance-sheet reasons independently of strategic or policy considerations.[24]

The above constraint is based on several assumptions and varies over time. It is assumed that the central bank balance-sheet items “other assets” (COA_0) and “other liabilities” (COL_0) are independent of all other balance sheet items. This may not be entirely correct given, for example, that any increase in the item “central bank credit” could lead to a higher amount under the item “other liabilities” (e.g. deposits held by certain non-banks that have access to the central bank balance sheet). It is also

[24] Brunnermeier and Niepelt (2019) define conditions under which the introduction of a CBDC would be neutral, i.e. would not alter the allocation and prices. One of these conditions is that the central bank always replaces all lost deposits with central bank funding and this central bank funding is offered to banks at the same conditions as deposits. The authors acknowledge that central bank funding is typically not offered at the same conditions as deposits given that it needs to be collateralised. We argue here that the central bank would not be able to replace all lost deposits with central bank funding if the deposit loss were to exceed a specific level.

assumed that the banking sector could use all its unencumbered eligible assets at the same time as collateral in central bank credit operations and that the central bank could theoretically purchase all eligible assets of non-banks. Moreover, in the event, for example, of valuation changes, new asset issuances or maturing assets, the variables on the right-hand side of Constraint 1 would change over time. The constraint should therefore be seen as a theoretical reference point that provides a broad illustration of how much CBDC-induced deposit losses would in principle be possible from the perspectives of the balance sheet of a central bank and of the aggregate balance sheets of the banking sector and of the non-bank sector.

For reasons related to monetary policy implementation, a central bank might wish to keep a positive level of reserves. Suppose, for example, that a central bank would like to keep the amount of reserves above a given level R_{min} because smooth implementation of monetary policy might otherwise be at risk (see Section 4). The amount of deposit losses (DL) would then be constrained by

$$(2)\quad DL \leq R_0 - R_{min} + (1-h) \cdot UBE_0 + NE_0.$$

For monetary policy reasons, a central bank might wish to maintain the ability to keep its financial asset portfolio below the amount that would be theoretically possible or even to reduce its financial asset portfolio. Suppose, for example, that a central bank would like to keep the option of reducing its financial asset portfolio to a given amount A_{min} with $A_{min} < A_0$. In this case, the amount of CBDC-induced deposit losses would need to be limited at a lower level. Instead of assuming that an amount of NE_0 could be additionally purchased, it would need to be assumed that the central bank could decide to offload financial assets in the amount of $A_0 - A_{min}$. If none of these assets were posted to commercial banks' balance sheets, the CBDC-induced deposit losses would be constrained by

$$(3)\quad DL \leq R_0 - R_{min} + (1-h) \cdot UBE_0 - (A_0 - A_{min}).$$

If some of the assets offloaded by the central bank were obtained by the banking sector, then these assets could be used by the banks as additional collateral for central bank credit. This could possibly increase the amount of deposit losses that could be tolerated from the perspective of the balance sheets.

The above considerations abstract from the situation of individual banks, which might face liquidity problems long before any constraints defined on the basis of aggregate balance sheets become binding. Banks have different levels of liquidity and would lose different amounts of deposits if a CBDC was introduced. That means that some banks might run out of liquidity although the banking sector in the aggregate still had abundant reserves. This could be an issue, in particular if banks with a liquidity surplus were not always prepared to lend reserves to banks with a deficit. In addition, regulatory liquidity constraints might become binding on individual banks. For example, the liquidity coverage ratio (LCR) of many banks might fall below the regulatory requirements as a result of bank deposits being converted into CBDC. It would therefore be advisable to complement the considerations surrounding Constraints 1 to 3 with an analysis on the level of liquidity of individual banks, which might point to a need for tighter constraints on CBDC-induced deposit losses.[25]

[25] See Meller and Soons (2023) who study empirically how deposit losses due to a fictitious introduction of a euro CBDC in 2021 might have impacted individual banks in the euro area. The authors find that the impact would have been contained, even in very adverse scenarios, if a holding limit of €3,000 per person, as suggested by Eurosystem officials (see Panetta, 2022), had been applied.

Box 2
High-level design choices of current CBDC initiatives across the globe

Many central banks worldwide are engaged in exploring and developing a retail CBDC, with varying levels of progress so far. According to a 2023 survey conducted by the BIS, 93% of respondent central banks reported involvement in some form of work on a CBDC.[26] The first central banks to issue a CBDC include those of Nigeria, the Bahamas, Jamaica, and the Eastern Caribbean Currency Union, while China and India are conducting pilot programs. Additionally, from the first half of 2023, 19 more central banks have been actively conducting experiments.[27] Major central banks, such as the Bank of England, the Bank of Canada and the ECB, are currently assessing the need for a retail CBDC while continuing their preparatory work. This Box collects and summarises publicly available information on a selection of CBDC projects to catalogue the high-level design choices they have made that are relevant from a monetary policy implementation perspective. Table 2 summarises this information.

Table 2
CBDC design choices

Central bank and CBDC name	**Project status**	**Remuneration**	**Limits**	**Interoperability with deposit account**
Euro area Digital euro	Investigation phase finished in October 2023 and preparation phase started in November 2023	Not decided. Current legislative proposals points to 0% remuneration[28]	Holding limit for individuals, possibly in the range of 3,000 to 4,000 euros,[29] and a zero holding limit proposed for businesses and governments[30]	Waterfall and reverse waterfall functionalities[31]
Bahamas Sand dollar	Live since October 2020	0%	3-tier model[32] with holding limits and monthly transaction limits for both consumers and merchants	Waterfall functionality is available, whereby any holdings exceeding the wallet's limit will flow into a deposit account
Canada	Public consultation	0%	Not specified	Not specified

26 See Kosse and Mattei (2023).

27 See Auer, Cornelli and Frost (2023), who compile a dataset of CBDC projects, speeches and search interest as of 1 July 2023.

28 See the legislative proposal for a digital euro, European Parliament and Council (2023).

29 See Panetta (2022).

30 See ECB (2023a).

31 European Central Bank (2022b).

32 A tiered limits model refers to the design choice to impose limits on transactions and/or holdings of CBDC, differentiating between users based on the level of information provided when a CBDC wallet is opened. Typically, CBDC users can opt for a wallet with low limits by providing minimal information and can upgrade to wallets with more relaxed limits by providing additional information, such as giving details of a linking bank account or providing a personal tax code.

China E-CNY	Pilot program launched in 2019 in major cities nationwide	0%	Tiered limits on both transactions and holdings	Not specified
Eastern Caribbean DCash	Live since March 2021	0%	Tiered limits on both transactions and holdings	Wallets can be obtained without a bank account
India Digital rupee	Pilot program ongoing (launched in December 2022) involving ten banks, over 1 million users and 260 thousand merchants.[33] Part of a phased implementation plan over 2022-2023[34]	0%[35]	Limits set by the distributing bank	Not specified
Jamaica JAM-DEX	Live since July 2022	0%	Tiered limits imposed by the wallet provider	The CBDC wallet is separate from any bank account and no waterfall mechanism is specified
Japan	A pilot program was launched in April 2023 after two proof of concepts (POC) projects (started in 2021 and 2022)	Undecided	Undecided but limits were explored in the POC projects	Undecided but waterfall functionality was tested in the POC projects
Nigeria eNaira	Live since October 2021	0%	4-tier model with holding limits and daily transaction limits. No limits are applied to merchants	Waterfall functionality is available
Norway	Experimentation is ongoing to identify a preferred technical solution for potential issuance	Undecided, but the monetary policy function of the CBDC is a desired feature[36]	Not specified	Not specified
Sweden E-krona	Proof of concept project ongoing. Assessment of the need for an e-krona in 2024	To be decided	To be decided	Not specified
UK Digital pound	Public consultation	0%	Proposed holding limit of GBP 10,000-20,000 but a lower limit is also considered	Waterfall functionality is being assessed

33 See Sankar (2023).
34 PIB (2022).
35 RBI (2022).

The four live CBDC projects are located in countries where financial inclusion is one of the main benefits, but circulation of issued CBDCs has so far remained moderate. The Central Bank of the Bahamas (CBB) was the first to issue a CBDC, the Sand Dollar, at the end of 2020. Despite the small size of the domestic economy, the CBDC has gained the attention of the public and policymakers as the first officially released CBDC worldwide. Adoption remains moderate (less than 1% of currency issued).[37] The Central Bank of Nigeria (CBN) announced the pilot roll-out of the eNAIRA in September 2021, officially launching it a year later in September 2022. In May 2022, the Bank of Jamaica announced the roll-out of its CBDC, JAM-DEX, which is provided to the public by wallet providers and not linked to customers' bank accounts. From February 2023, JAM-DEX onboarded 190,000 customers and had a total transaction activity valued at JMD 357 million (EUR 2.1 million) in 2022. In March 2021 the Eastern Caribbean Central Bank (ECCB) launched its DCash pilot program in several ECCB member countries. After experiencing technical difficulties between January and March 2022 that resulted in an interruption of service, the ECCB announced in November 2022 that it would continue to support the use of DCash.

While few central banks have yet announced the roll-out of a CBDC, research efforts are ongoing in most developed economies. The major world economy with a CBDC at an advanced stage of development is China, where programs are currently being conducted in several Chinese provinces. The People's Bank of China has not yet announced a timeline for the final roll-out of the e-CNY. The Reserve Bank of India (RBI) launched a retail CBDC pilot program on 1 December 2022 involving over a million users and 262,000 merchants[38], which continued in the course of 2023. The Bank of Canada is developing the capacity to issue a retail CBDC as a contingency plan to address a potential decline in the use of cash, or a widespread adoption of alternative digital currencies, with the aim of preserving the desirable features of the current payment ecosystem.[39] In Europe, one of the first central banks to start researching a CBDC was the Sveriges Riksbank in Sweden, which published its first report on the e-krona in 2017.[40] No clear timeline for the issuance of the e-krona has been announced but the Sveriges Riksbank has been invited to submit a petition to the Swedish parliament in 2024 to determine whether there are sufficient grounds for issuing the e-krona. The Eurosystem ended a two-year investigation phase into a digital euro in October 2023 in which key issues regarding the CBDC’s design and distribution were considered. The investigation phase will be followed by a preparation phase that will address the technical implementation issues and the testing of a digital euro.[41] In June 2023 the European Commission submitted a legislative proposal on the establishment of the digital euro. The Bank of England published a public consultation[42] in February 2023 on the policy case for issuing a digital pound. After the consultation closes, the Bank of England anticipates a two to three-year design phase.[43] No decision has been taken yet on whether there is need for a digital pound. The Bank of

[37] See Hall (2022).
[38] See Sankar (2022).
[39] See Bank of Canada (2020).
[40] See Sveriges Riksbank (2017).
[41] See ECB (2023b).
[42] See Bank of England (2023a).
[43] See Bank of England (2023b).

Japan started a piloting phase in April 2023 after conducting two proof of concept experiments in 2021 and 2022 but has not so far committed to the issuance of a CBDC.

So far, all live CBDCs and advanced pilot projects have opted not to remunerate CBDC holdings, reinforcing the notion that CBDCs are a digital equivalent of physical cash. The remuneration of CBDCs could vary depending on the design and policies implemented by each central bank. Generally, CBDCs have been promoted as fulfilling the same essential payments purposes as physical cash and, as such, they typically do not bear interest. Nonetheless, a central bank could decide to remunerate its CBDC to modulate its demand or to use it for the implementation of its monetary policy stance. Currently, all live CBDCs have opted for zero remuneration, and a similar stance has been adopted by projects in advanced stages of development, such as the e-CNY in China and the Digital Rupee in India. Zero remuneration is also suggested in the current proposal by the European Commission for a digital euro. The debate on CBDC remuneration is, however, ongoing, with alternative remuneration models still being explored: Norges Bank published reports in 2019 and 2020 outlining how using its potential CBDC as a monetary policy instrument is among the desired features that the bank is using to evaluate different options for technical implementation.

Many central banks are opting to impose limits on CBDC transactions and holdings to curb the risk of a sudden outflow of bank deposits into CBDC. Our review highlights three models adopted by central banks. The first model does not impose formal limits on CBDC holdings but instead leaves risk management and any limitation of excessive use to the wallet providers – the intermediaries providing the interface between end-users and the central bank. This is the case for the Bank of Jamaica's JAM-DEX and India's Digital Rupee. A second model, applied by many of CBDC projects under analysis, sets tiered limits on transactions and/or holdings based on Know Your Customer practices. Users can typically opt for the lowest limit by providing minimal information to CBDC distributors and can upgrade to higher limits by providing additional details. Projects applying this model include those of Nigeria, the Bahamas, the Eastern Caribbean and China. The last model, discussed within the framework of the digital euro and digital pound projects, identifies a pre-set hard limit on holding digital currency, often coupled with waterfall functionalities to prevent transaction failures if the limit is reached.

4 CBDC and the smooth implementation of monetary policy

A CBDC might not only change the amount of reserves that the banking sector actually holds, but also the amount of reserves required for smooth implementation of monetary policy. In the previous section, we have argued that a CBDC that entails a loss of commercial bank deposits could lead to a reduction in the reserves held by the banking sector, i.e. a reduction in the supply of reserves. This is qualitatively, although not necessarily quantitatively, identical to the impact on the central bank balance sheet of bank deposits being converted into banknotes. In this section, we will argue that a CBDC could also result in an increase in the demand for reserves by the banks, an effect specific to the introduction of a CBDC. This would mean an increase in the amount of reserves required for smooth implementation of monetary policy, i.e. for an effective steering of short-term money market rates by the central bank.[44]

In our analysis, we look at two stylised types of systems for the implementation of monetary policy: the floor system and the corridor system. One of the main objectives of monetary policy implementation is to steer interest rates in the short-term money market to the level that is considered appropriate for monetary policy stance reasons. While a multitude of systems are conceivable for achieving this objective, there are two that tend to prevail: the floor system and the corridor system. These stylised systems broadly encompass the main types of frameworks that have been used by major central banks up to now and are therefore useful in illustrating the mechanisms at play in these key frameworks. In Sub-section 4.1 below, we discuss the impact of a CBDC on monetary policy implementation based on a floor system. Sub-section 4.2 looks at the case of a corridor system.

4.1 Floor system

In a floor system, the central bank steers short-term money market rates close to the rate it pays on overnight reserves (the deposit rate). To achieve this, the banking sector needs to hold sufficiently large reserves. Let us suppose that for monetary policy reasons a central bank considers that the interest rate in the short-term money market should be at a given level $\hat{r}$. If the central bank implements monetary policy through a floor system, then it makes r_D, the rate at

[44] There are scarcely any academic studies looking at the impact of a CBDC on money market rates and the consequences for monetary policy implementation. Exceptions to this are Meaning et al (2021), Section 4.3 in Ahnert et al (2022), Lamersdorf et al (2023) and Abad et al (2023). See also Nessén (2018) for a discussion in relation to the Sveriges Riksbank's e-krona project.

which it remunerates overnight reserves held by banks with the central bank (the deposit rate) equal to $\hat{r}$. It then provides reserves (through credit or outright operations) in the amount needed to ensure that there would be a liquidity supply surplus in the short-term market at any rate above the deposit rate. The market rate would thus fall until it equals the deposit rate so that banks would be indifferent about whether to offer liquidity in the market or hold reserves with the central bank, i.e. money market equilibrium is reached, with the market rate being at the deposit rate. This means that banks do not face a (significant) opportunity cost in holding central bank reserves rather than lending in the market.[45]

If the introduction of a CBDC were to entail a loss of commercial bank deposits, resulting in a reduction of reserves held by the banking sector (see Section 3.1), short-term market rates could increase to levels significantly above the deposit rate. This situation is illustrated in Chart 7a. The chart shows the relationship between the reserves held by banks and the short-term money market rate. While there are still ample reserves (R_1), the money market rate (r_1) remains at the deposit rate. If the reserves decline (R_2), for example due to the introduction of a CBDC, an increasing number of banks would be faced with a shortage of reserves and would try to borrow reserves in the money market. This would drive the money market rate up (r_2). The threshold amount of reserves below which market rates increase as reserves decline is the minimum amount of reserves required for the smooth implementation of monetary policy through a floor system (the floor required excess liquidity or FREL).

The central bank could provide additional amounts of reserves to push the money market rate down to the deposit rate again. This would require central bank credit to be offered at favourable rates or additional asset purchases to be made by the central bank. The central bank could, in principle, provide more reserves through (i) granting additional credit to banks and (ii) making asset purchases. For option (i) to work, however, the (marginal) interest rate at which the central bank provides credit would need to be close to, or at, the deposit rate.[46] Otherwise, even if short-term money market rates were above the deposit rate due to a shortage of reserves, they might still be below the rates on central bank credit. Most banks might then prefer to borrow reserves in the market rather than from the central bank. Only banks with limited access to the money market or that benefit more from central bank borrowing than from short-term market funding, e.g. due to regulatory reasons,[47] would demand credit from the central bank. This

[45] For a detailed discussion of the floor and the corridor system, see Aberg et al (2021).

[46] In the euro area, for example, the interest rate on regular central bank credit operations is currently 50 basis point above that on the deposit rate. By contrast, the Bank of England provides liquidity to eligible counterparties at the bank rate, the rate at which it also remunerates reserves.

[47] For example, borrowing from the central bank against collateral not qualifying as high-quality liquid assets improves the liquidity coverage ratio (LCR) of a bank, while even unsecured short-term market funding may not improve the LCR. This is because short-term market funding increases the LCR numerator and denominator by the same amount.

borrowing might not generate sufficient additional reserves to return the market rate back down to the deposit rate. To ensure that there is sufficient demand for central bank credit, the credit conditions offered by the central bank would therefore need to be sufficiently favourable (e.g. a relatively low interest rate, possibly combined with a long maturity). If this was not considered desirable, the central bank would then need to resort to option (ii), i.e. conduct asset purchases of, for example, government bonds.[48]

Chart 7

CBDC impacting money market rates through two channels

Chart 7a: The conversion of bank deposits into CBDC could push excess liquidity below the amount required to anchor money market rates.

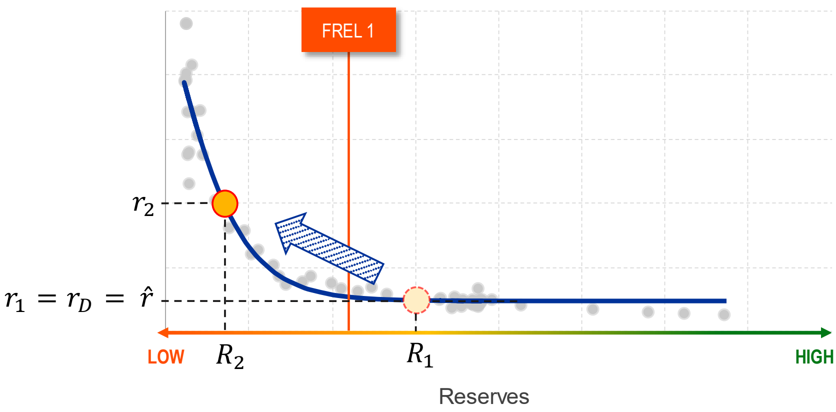
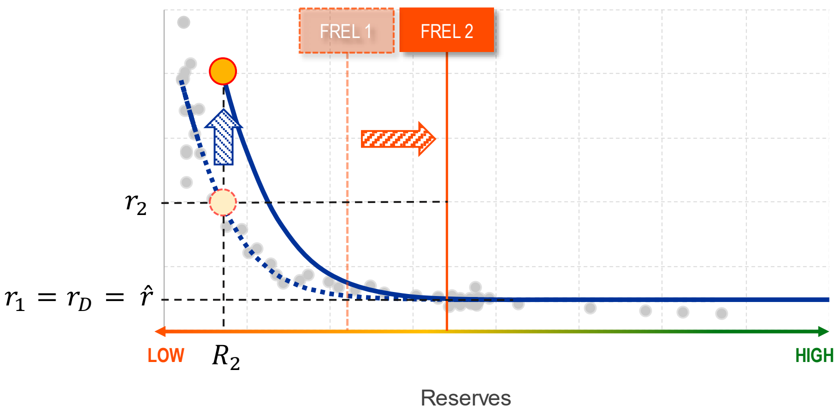


Chart 7b: The CBDC could also increase bank demand for liquidity, moving the FREL higher.



48 See Section 3 of Meaning et al (2021) and Abad et al (2023) for analyses related to that undertaken in this and the previous paragraph.

In a floor system, the introduction of a CBDC may not only entail a reduction in reserves, but also an increase in the amount of reserves needed for the smooth implementation of monetary policy. Even in the absence of minimum reserve requirements, banks may need to hold reserves for different reasons. For example, bank customers are able to withdraw deposits in the form of cash or CBDC at any time, including at times when the central bank does not offer new liquidity through monetary policy operations. This may require banks to build up a reserve buffer in the days before. This reserve buffer may need to be higher after a CBDC has been introduced because the CBDC may increase the uncertainty about withdrawals. Indeed, the maximum amount of deposit withdrawals might be higher in a world with a CBDC. Consequently, the introduction of a CBDC might shift to the right the curve describing the relationship between reserves and market rates, as shown in Chart 7b. In a floor system, this shift would mean an increase in the required amount of reserves (as shown in Chart 7b by the move from FREL 1 to FREL 2).

In Box 3, we use a simple general equilibrium model to study different situations in a floor system under which a CBDC would increase the reserves needed for smooth implementation of monetary policy. A very simple situation is the weekend case. If bank customers were to withdraw bank deposits on weekends, then banks would need to have sufficient reserves over the weekend to cater for the withdrawals that could be reasonably expected. These reserves would need to be obtained before the weekend given that new reserves could not be obtained from the central bank or in the market over the weekend. Banks would therefore need to hold reserves before the weekend started. If the central bank did not offer sufficient reserves to this end, market rates would increase above the deposit rate shortly before the weekend began. This would not be in line with a smooth monetary policy implementation. If a CBDC was introduced, bank customers could then withdraw deposits in the form of CBDC over weekends. The maximum amount of withdrawals might increase (even though the expected amount might not), requiring larger reserve buffers to be built up before the weekend. A similar situation could arise on a weekday on which the central bank does not provide new reserves, even though banks could borrow in the money market. In that case, to avoid money market rates increasing above the deposit rate if customers were to withdraw large amounts of deposits, the central bank would need to have provided sufficient reserves in advance of any day on which new reserves would not be offered, the level of those reserves potentially being higher in a world with a CBDC.

Central banks have different options available to them to reduce the additional reserves that banks might need to hold as a result of a CBDC. For example, they could offer new reserves at the same conditions on a daily basis so that precautionary reserve buffers would not be needed. This might not, however, be possible on weekends. Central banks could also design a CBDC in a way that would limit deposit outflows. One way of doing this would be to apply sufficiently tight CBDC holding limits for all CBDC users.

Box 3

Model showing the impact of a CBDC on the amount of reserves needed for smooth implementation of monetary policy: floor system

In this box, we present a model of monetary policy implementation in a floor system.[49] We use the model to study the impact of a CBDC on the reserves that the banking sector would need to hold with the central bank to ensure that short-term money market rates could be securely anchored to the rate at which the central bank remunerates reserves (the deposit rate). Our model is a very simple general equilibrium model with two periods ($t = 1, 2$). For the purposes of this model, there is one representative bank, bank customers with deposits held in that bank, and a central bank. There are no minimum reserve requirements to be fulfilled by the bank.

In period $t = 1$, the bank has an initial endowment of central bank reserves of $R_0 + A_0$. The component A_0 is the result of asset purchases by the central bank from bank customers before $t = 1$. (Such purchases lengthen the bank's balance sheet as they increase the level of customer deposits held with the bank and the reserves held by the bank with the central bank). The component R_0 is the amount resulting from other activities. We assume that the central bank has preannounced that it will provide the amount A_0 in reserves through asset purchases and that it does not deviate from this, i. e. it will not conduct any asset purchases in $t = 1$ and in $t = 2$. The amount A_0 is the main policy parameter for the central bank in its effort to steer money market rates in line with its intended monetary policy stance. It sets A_0 at a level that ensures that monetary policy can be implemented in a floor system.

In $t = 1$ the bank can borrow from the central bank any amount it wishes at the policy rate r_M and can borrow (or lend) in the unsecured interbank market at the rate r_1. $CC_1 \geq 0$ is the amount the bank borrows from the central bank and CI_1 the amount borrowed (or lent if $CI_1 < 0$) in the interbank market. The bank then has reserves of $R_1 = R_0 + A_0 + CC_1 + CI_1$ at the end of period $t = 1$. Given that there is just one (representative) bank, we will have $CI_1 = 0$ in equilibrium. The bank can borrow from the central bank only against eligible collateral. For simplicity, we assume that collateral constraints are always non-binding: the bank always has enough eligible collateral to collateralise whatever amount it wishes to borrow from the central bank. The bank can hold reserves overnight with the central bank at a rate of r_D (the deposit rate). We assume $r_M > r_D$. For simplicity, we normalise $r_D = 0$.

In period $t = 2$, customers of the bank purchase goods and services for an amount of Q, of which an amount $c \cdot Q$ will be paid with central bank money, i.e. cash or CBDC. To do so, they convert an equal amount of bank deposits into central bank money, resulting

[49] The stylised case of a floor system that we consider here, where the central bank aims to ensure a sufficient amount of reserves through asset purchases, is often referred to as a "supply-driven" floor system.

in a loss of reserves in this amount for the bank.[50] The amount Q is a random variable distributed over an interval $[Q_l; Q_h]$. The parameter c will be decisive and we assume that it will increase when the central bank introduces its CBDC, as discussed in Section 3. We also assume that $cQ_h > R_0$ and that the bank has to ensure that it always has sufficient reserves to convert as many deposits into central bank money as customers wish.

We now study two variants. In the first variant, period $t = 2$ is a weekend. In the second variant, it is a weekday without central bank lending operations.

The weekend case

We first assume that period $t = 2$ is a weekend: the central bank and the interbank market are closed and the bank cannot obtain new reserves from the central bank. Borrowing and lending transactions conducted in $t = 1$ mature (and pay interest) only after $t = 2$. The reserves R_1 that the bank holds with the central bank at the end of $t = 1$ are also the reserves it has available at the start of $t = 2$. The bank has to raise sufficient reserves already in $t = 1$ to be able to satisfy all possible customer requests in $t = 2$, even if $Q = Q_h$, i.e. it needs to fulfil the constraint

(1) $(R_1 =) R_0 + A_0 + CC_1 + CI_1 \geq cQ_h.$

With a floor system, to implement monetary policy the central bank needs to set its policy parameter A_0 such that $r_1 = r_D$. The following result, which is proved in the annex, summarises what the central bank needs to do to this end:

RESULT 1: There is an equilibrium with $r_1 = r_D$ if, and only if, $A_0 \geq cQ_h - R_0 \equiv A_0^*$.

Thus, the central bank needs to set A_0 sufficiently high to ensure that the bank does not need to borrow reserves in $t = 1$. It may, through asset purchases, provide more reserves than what the bank needs. Where this is the case, those excess reserves should be kept by the bank with the central bank in $t = 1$ rather than offered in the market. To ensure this, the market rate needs to equal the deposit rate ($r_1 = r_D$).

Since A_0^* is increasing in c, introducing a CBDC under a floor system would increases the minimum amount of assets to be purchased by the central bank. The minimum reserve levels required in such a system in periods $t = 1$ and $t = 2$ respectively are:

$$R_1^* \equiv R_0 + A_0^* = cQ_h$$

and

$$R_2^* \equiv R_0 + A_0^* - cQ = c(Q_h - Q).$$

[50] For simplicity, we assume that the bank can keep all its central bank money in its central bank reserve account until bank deposits are converted into central bank money, i.e. the bank does not need to keep a vault of cash but can obtain cash from its central bank reserve account in real time. Before a weekend, commercial banks normally need to withdraw sufficient cash from their reserve accounts to fill up ATMs ready for weekend use. However, we assume here that this is not needed even for weekends.

Obviously, introducing a CBDC increases the minimum amount of reserves in both periods. The additional reserves need to be provided by the central bank through asset purchases given that the bank will not demand any central bank credit ($CC_1 = 0$).

Note that in our model, uncertainty can be measured by the distance $cQ_h - cQ_l$. The uncertainty does not, however, have any impact on R_1^* (given that it depends solely on cQ_h and not on cQ_l). Reserves are not held in period $t = 1$ as a buffer catering for uncertainty. The situation is different for the reserves R_2^* in period $t = 2$, which are zero if there is no uncertainty (i.e. $cQ_h = cQ_l$) and positive otherwise.

The weekday case:

As a second variant, we assume that period $t = 2$ is not a weekend, but a normal weekday. However, the central bank does not offer new reserves in $t = 2$. As in the weekend case, borrowings from the central bank in $t = 1$ mature after $t = 2$ (when the central bank conducts the next lending operation). There is now an unsecured overnight interbank market in both periods (with rate r_t in period t). Borrowings in the market in $t = 1$ (CI_1) mature in $t = 2$ and borrowings in the market in $t = 2$ (CI_2) mature after $t = 2$. In $t = 2$, the bank will need to fulfil the constraint

(2) $R_2 = R_0 + A_0 + CC_1 + CI_1 - (1 + r_1) \cdot CI_1 + CI_2 - c\mathrm{Q} \geq 0.$

With a floor system, to implement monetary policy he central bank would need to set its policy parameter A_0 such that $r_1 = r_2 = r_D$. The following result (see the annex for the proof) describes the action required of the central bank:

RESULT 2: There is an equilibrium with $r_1 = r_2 = r_D$ for all $Q \in [Q_l; Q_h]$ if, and only if, $A_0 \geq cQ_h - R_0 \equiv A_0^*$.

If $A_0 < A_0^*$, then there may be an equilibrium with $r_1 = r_2 = r_D$ if Q turns out to be sufficiently low (more precisely: if $A_0 \geq cQ - R_0$). But if Q turns out to be high (if $A_0 < cQ - R_0$), then there is no equilibrium with $r_1 = r_2 = r_D$. This is so because if $r_1 = r_2 = r_D$ and $A_0 < A_0^*$, then the bank would not borrow any reserves in $t = 1$ but would wait to see if it needs reserves in $t = 2$; if it did, it would borrow them in the market. This would not be an equilibrium.

Apart from this point, we get results for the weekday case that are similar to those for the weekend case: in order to establish a floor system, the central bank needs to set A_0 above the threshold A_0^* so that the excess reserves in $t = 1$ and $t = 2$ are above the thresholds R_1^* and R_2^*. Introducing a CBDC increases the minimum amount of assets to be purchased by the central bank and the minimum amounts of reserves in periods $t = 1$ and $t = 2$ required in a floor system. The bank will not borrow any reserves from the central bank. The model therefore supports the arguments set out in the main text of Section 4.1.

4.2 Corridor system

In a classic corridor system, the central bank steers short-term money market rates to the midpoint between the rate it pays on overnight reserves (the deposit rate) and the rate it charges on overnight borrowings (the lending rate). Suppose that the central bank considers, from a monetary policy perspective, that the interest rate in the short-term money market should be at a given level $\hat{r}$. If the central bank implements monetary policy through a corridor system, it would then set r_D, the deposit rate, at a spread s below $\hat{r}$. And it would set r_L, the lending rate, at a spread s above $\hat{r}$. It could then aim to provide the amount of central bank liquidity with which the short-term money market clears at the rate $\hat{r}$, the midpoint of the corridor between r_L and r_D. The central bank could provide the liquidity through regular term credit operations (offering credit with maturities beyond overnight), for example at a fixed rate of $r_M = \hat{r}$. It could also conduct "fine-tuning" operations on an ad hoc basis to absorb or lend liquidity in case the market does not clear at $\hat{r}$. Overall, in this system, the central bank aims to maintain balanced liquidity conditions, meaning that it supplies the reserves demanded by banks if the market rate is $\hat{r}$. But holding excess central bank reserves (remunerated at r_D) entails an opportunity cost given that those reserves could be lent out in the money market at a higher rate.

In a corridor system, the central bank could require banks to hold a minimum level of reserves with the central bank (minimum reserve requirements) on average over a specific period (the maintenance period) in order to generate a standing demand for central bank reserves that facilitates interest rate control. The averaging mechanism of reserve requirements functions as a buffer against liquidity shocks. If the banking sector loses large amounts of reserves on a specific day of the maintenance period, banks do not need to rush to the money market to borrow reserves but can, instead, simply temporarily reduce their minimum reserve holdings and make up for the under-fulfilment in the remaining part of the maintenance period. Conversely, if the banking sector receives large amounts of reserves, banks do not need to lend reserves in the market but could instead temporarily overfulfil their minimum reserve requirements and then undershoot the requirement by an equivalent amount in the rest of the maintenance period. Minimum reserve holdings could be remunerated. If the central bank offers term credit at a fixed rate $r_M = \hat{r}$, minimum reserve holdings are remunerated at the rate r_M and reserve requirements are sufficiently large, then banks could not only borrow (term credit) from the central bank at r_M, but also keep reserves with the central bank at r_M. Consequently, the market rate would also be close to r_M.

If the introduction of a CBDC were to entail a loss of commercial bank deposits, resulting in a reduction in the reserves held by the banking sector, banks would then borrow more from the central bank. While in a floor system the loss of deposits would require the central bank to provide additional reserves through central bank credit at favourable rates or through asset purchases (see Section 4.1 above), this might not be needed in a corridor system. Instead, banks would be happy to borrow reserves from the central bank at the rate $r_M = \hat{r}$ which is close to the market rate.

The introduction of a CBDC might also result in greater volatility of money market rates owing to greater volatility of reserves - an issue that could be addressed through various strategies in a corridor system if it was deemed problematic. Once a CBCD has been introduced, bank customers will be able to withdraw deposits at any time not only in the form of cash, but also in CBDC. Consequentially, the possibility that a CBDC might increase the number and severity of liquidity shocks cannot be ruled out. Should the resulting volatility be undesirable and impact monetary transmission, the central bank could address it by conducting more frequent fine-tuning operations or narrowing the corridor between the deposit and lending rates. As argued above, minimum reserve requirements with an averaging mechanism may serve as a buffer against liquidity shocks in a corridor system. This suggests that in a corridor system a central bank that uses minimum reserve requirements with an averaging mechanism could address any higher volatilities stemming from a CBDC through higher minimum reserve requirements.

In Box 4, we adjust the simple general equilibrium model introduced in Box 3 to study different situations in which a CBDC might have an impact on the optimal level of minimum reserve requirements in a specific type of corridor system. We assume that the central bank offers term credit at a rate r_M equal to the midpoint of the corridor, conducts asset purchases, applies minimum reserve requirements with an averaging mechanism and remunerates minimum reserve holdings at r_M. Suppose now that a weekday t is approaching on which the central bank does not offer new credit (or only at the high lending rate r_L). Bank customers can withdraw cash on day t. For that reason, the banking sector will increase its reserve holdings before day t. The additional reserves need to be stored temporarily until t. If all minimum reserve requirements have already been fulfilled, keeping the reserves at the central bank would mean remuneration at the low deposit rate r_D, i.e. the banks would prefer to lend the reserves in the market until t. This would result in a liquidity supply surplus and market rates would fall below r_M before t. If there are still minimum reserve requirements to be fulfilled, the banks could instead use their reserves to fulfil the requirements without offering them in the market, leaving the market rate close to r_M. Next, consider day t and assume that customers withdraw much less cash than expected, i.e. the banks have plenty of reserves. If there are still minimum reserve requirements to be fulfilled, the banks would not need to offer reserves in the market but could instead fulfil more minimum reserve requirements, preventing the market rate from falling below r_M. Now suppose that a CBDC is introduced. Bank customers could still withdraw deposits in the form of cash, but now also in the form of CBDC. The potential amount of withdrawals may increase (see the discussion in Section 3), requiring larger reserve buffers. This would mean that the minimum reserve requirements set by the central bank would need to be higher in a world with a CBDC.

The central bank has similar options as in a floor system for reducing any additional reserves that banks might need to hold owing to the CBDC. For example, the central bank could offer new credit at the rate r_M daily so that precautionary reserve buffers would be smaller. It could also apply sufficiently tight CBDC holding limits to all CBDC users.

Box 4

Model showing the impact of CBDC on the amount of reserves needed for smooth implementation of monetary policy: corridor system

In this box, we present a model of monetary policy implementation with a corridor system. The model is similar to that of Box 3. It is a very simple general equilibrium model with one representative bank, bank customers with deposits held in the bank, and a central bank. However, our model now has three periods ($t = 1, 2, 3$). We assume that the central bank imposes minimum reserve requirements on the bank. The bank has to hold reserves that add up to no less than M over the three periods that together make up the maintenance period. That means that the bank has to fulfil the constraint

(1) $R_1 + R_2 + R_3 \geq M$.

Here, R_t are the reserves held by the bank with the central bank overnight from period t to period $t + 1$. As in the model in Box 3, the bank has an initial endowment of central bank reserves of $R_0 + A_0$ at the start of period $t = 1$. The components A_0 and R_0 have the same interpretations as in Box 3. The policy parameters M and A_0 are set before period $t = 1$ to ensure that monetary policy can be implemented in a corridor system.

As in Box 3, in $t = 1$ the bank can borrow from the central bank any amount it wishes at the policy rate r_M and can borrow (or lend) in the unsecured interbank market at the rate r_1. The bank has reserves of:

(2) $R_1 = R_0 + A_0 + CC_1 + CI_1$

at the end of period $t = 1$. Given that there is just one (representative) bank, we will have $CI_1 = 0$ in equilibrium.[51]

In period $t = 2$, customers of the bank purchase goods and services for an amount of Q, of which an amount $c \cdot Q$ will be paid with central bank money (cash or CBDC). To do this, they convert an equal amount of bank deposits into central bank money. The amount Q is a random variable distributed over the interval $[Q_l; Q_h]$. The parameter c will increase if the central bank introduces a CBDC. We assume that $cQ_h > R_0$.

In period $t = 3$, the bank can again borrow (or lend) in the unsecured interbank market at the rate r_3. The central bank now conducts a fine-tuning operation, meaning that the bank can either borrow from the central bank at the policy rate r_M or lend to the central bank at the policy rate, depending on what is needed to implement monetary policy in a corridor system, i.e. what is needed to achieve $r_3 = r_M$. This assumption means that regardless of what happens in the first two periods, the bank will be able to fulfil its reserve requirements during the maintenance period and the equilibrium rate in period $t = 3$ will be $r_3 = r_M$.

Required reserves are remunerated by the central bank at the policy rate r_M. Excess reserves are remunerated at a rate of r_D (the deposit rate), with $r_M > r_D$.

[51] As in Box 3, the bank can borrow from the central bank only against eligible collateral, but we again assume that collateral constraints are always non-binding.

As in Box 3, we now study two variants. In the first variant, period $t = 2$ is a weekend. In the second variant, it is a weekday without central bank lending operations.

The weekend case

In the weekend case, the central bank and the interbank market are closed in $t = 2$ so that the bank cannot obtain fresh reserves. The bank has to raise sufficient reserves already on $t = 1$ to be able to satisfy in $t = 2$ all possible customer requests, i.e. it needs to fulfil the constraint

(3) $R_2 = R_0 + A_0 + CC_1 + CI_1 - cQ_h \geq 0.$

We assume here that borrowings from the central bank do not mature on weekends and also that the central bank does not credit interest payments on reserves during that period, but only in $t = 3$.[52]

To implement monetary policy in a corridor system, the central bank needs to set its policy parameters A_0 and M such that $r_1 = r_M$. The following result (proof in the annex) summarises what the central bank needs to do to this end.

RESULT 3: There is an equilibrium with $r_1 = r_M$ if, and only if, $A_0 \leq \max\left\{cQ_h; \frac{M+cQ_l}{2}\right\} - R_0 \equiv A_0^+$.

If $A_0 > A_0^+$, then A_0 is so high that (i) condition (3) is fulfilled even with $CC_1 = CI_1 = 0$, and (ii) the bank would overfulfil its reserve requirements in $t = 2$, at least if $Q = Q_l$, without lending funds in the market. Because the excess reserves are remunerated at the low rate r_D, the bank would lend in the market if $r_1 = r_M$. Given that an equilibrium requires that $CI_1 = 0$, $A_0 > A_0^+$ would not give an equilibrium with $r_1 = r_M$. If, however, $A_0 \leq A_0^+$, then an equilibrium with $r_1 = r_M$ would exist. In this equilibrium, the bank would be happy to borrow from the central bank at least $CC_1 = cQ_h - (R_0 + A_0)$.[53]

Given that A_0^+ is increasing in c, introducing a CBDC would increase the maximum amount of assets that the central bank could purchase given a level of reserve requirements M. And it would increase the lowest level of reserve requirements given an amount of purchases A_0.

The reserves in period $t = 1$ are:

$$R_1 = R_0 + A_0 + CC_1 \geq cQ_h = R_1^*.$$

R_1^* is obviously increasing in c, i.e. introducing a CBDC increases the lowest possible amount of reserves in period $t = 1$ in a corridor system. In contrast to in a floor system, these reserves are used to fulfil reserve requirements, i.e. they are not excess reserves.

52 As a result, we have (assuming that the bank does not hold excess reserves) $R_3 = R_1 \cdot (1 + r_M)^2 - cQ \cdot (1 + r_M) - CC_1 \cdot (1 + r_M)^2 - CI_1 \cdot (1 + r_1)^2 + CC_3 + CI_3$.

53 More precisely, the bank would choose $CC_1 \in [cQ_h - (R_0 + A_0); \max\{cQ_h; \frac{M+cQ_l}{2}\} - (R_0 + A_0)]$. That means that it could borrow more than $cQ_h - (R_0 + A_0)$ if $\mathrm{M} > cQ_h$ given that this would not immediately create excess reserves.

It should be noted that reserve requirements are not needed in the weekend case given that $A_0 < A_0^+$ can be fulfilled with $M = 0$. In the weekday case, however, zero reserve requirements would not be possible, as we will now see.

The weekday case:

As a second variant, we assume that period $t = 2$ is not a weekend and the money market is open, but the central bank does not conduct any operations. It offers an overnight lending facility, but the lending rate r_L is unattractive being high compared with the money market rate r_M. The level of the minimum reserve requirements is now essential for achieving an equilibrium with $r_1 = r_2 = r_M$. Given that there is now an interbank market in $t = 2$, the bank does not need to raise sufficient liquidity for period $t = 2$ already in $t = 1$. It could, instead, borrow whatever it needs in the market in $t = 2$. But this would not be an equilibrium. For an equilibrium with $r_1 = r_2 = r_M$ and $CI_1 = CI_2 = 0$, the central bank would need to establish a situation in which it is not disadvantageous for the bank to fulfil the condition

(4) $R_1 = R_0 + A_0 + CC_1 \geq \frac{cQ_h}{1+r_M}$.

If it does, the bank would, in any case (i.e. even if $Q = Q_h$), have sufficient reserves in $t = 2$, even without borrowing new reserves in that period. Moreover, the central bank would need to ensure that it did not result in the bank having excess reserves that it then offered in the market. This requires M to be sufficiently large.

RESULT 4: There is an equilibrium with $r_1 = r_2 = r_M$ for all $Q \in [Q_l; Q_h]$ if, and only if, $M \geq \max\left\{(2 + r_M)(R_0 + A_0) - cQ_l; \frac{cQ_h}{1+r_M} + c(Q_h - Q_l)\right\} \equiv M^*$.

If $(2 + r_M)(R_0 + A_0) - cQ_l > \frac{cQ_h}{1+r_M} + c(Q_h - Q_l)$, then the bank does not need to borrow reserves even if $Q = Q_h$. Given that M is sufficiently high, the bank does not lend funds in the market but instead uses them to fulfil reserve requirements. This suggests that the central bank can choose any level of asset purchases A_0 provided it sets the reserve requirements M sufficiently high. Obviously, M^* is decreasing in c, i.e. introducing a CBDC reduces the necessary level of minimum reserve requirements in a corridor system if A_0 is so large that the bank does not need to borrow reserves. This is because a CBDC absorbs some reserves from the market so that this does not need to be done through higher reserve requirements.

More relevant for a corridor system appears to be a case with relatively low central bank asset purchases. If $(2 + r_M)(R_0 + A_0) - cQ_l < \frac{cQ_h}{1+r_M} + c(Q_h - Q_l)$, then the bank would need to borrow some funds, at least if $Q = Q_h$. It does so already in $t = 1$ and from the central bank. Again, as M is sufficiently high, the bank does not lend funds in the market but instead uses them to fulfil reserve requirements. Now, M^* is increasing in c, i.e. introducing a CBDC increases the necessary level of minimum reserve requirements in a corridor system if A_0 is so low that the bank needs to borrow reserves.

Instead of using minimum reserve requirements, the central bank could, of course, also offer (overnight) credit at the rate r_M including in $t = 2$ (or opt for a zero corridor).

5 Conclusions

A CBDC would introduce a new liability, potentially of significant size, on the issuing central bank's balance sheet, thereby raising the possibility that its reserve management, interest rate control and, more broadly, the way in which it implements monetary policy would be affected. If this new form of money were to merely replace the more traditional kind, namely banknotes, there would be no significant implications for monetary policy implementation. If, however, users of CBDC ask to convert some of their bank deposits into this new instrument, banks would need to finance the conversion by using their holdings of central bank reserves. This would lead to a reduction in the overall amount of reserves in the system if the central bank did not provide additional liquidity.

While the basic balance-sheet mechanics of bank deposit conversion to CBDC are qualitatively similar to those that apply in the case of banknotes, CBDC has the potential to involve larger volumes of conversion and to also affect banks' demand for central bank reserves. Unlike banknotes, CBDC is not subject to safekeeping and insurance costs, which suggests that, in the absence of holding limits, the potential for users to amass large amounts of this instrument could be considerable. Similarly, costless and straightforward conversion of bank deposits into and out of CBDC could result in conversion occurring at great speed and in a way that could not be easily predicted, especially given the lack of historical data for establishing usable patterns for such conversions. As a result, the current paper shows that not only could the amount of reserves available in the system be significantly reduced, but the minimum volume of reserves required to effectively steer short-term money market rates might also turn out to be higher. This would lead to a need for the central bank to supply more reserves to the system, which, in turn, would be subject to constraints such as those arising from collateral availability.

CBDC design features, such as those envisaged for the digital euro, that directly affect the ease of conversion into and out of CBDC and the overall amount that may be held, could be decisive in limiting the extent to which the introduction of a CBDC might complicate monetary policy implementation. Features such a waterfall and reverse waterfall for the conversion of bank deposits into and out of CBDC would greatly improve ease of conversion and, as argued in the current paper, could, in fact, boost demand for bank deposits by reducing the amount of all types of central bank money (banknotes and CBDC) that agents in the economy might need to hold at any point in time in order to accommodate their payment needs. Similarly, quantitative holding limits would guard against the build-up of an unduly sizeable volume of CBDC on users' electronic wallets. While these features are primarily intended to serve purposes such as ensuring the usability of

CBDC and minimising any negative side effects on bank intermediation, this paper has shown that they would also help to address the risk of interference with monetary policy implementation that could otherwise arise from the introduction of a CBDC.

Proofs of results 1 to 4

RESULT 1

Suppose that $A_0 < cQ_h - R_0$ and $r_1 = r_D (= 0 < r_M)$. The bank would need to borrow reserves in $t = 1$. Since $r_1 < r_M$, it would do so in the market. Thus, there is no equilibrium with $r_1 = r_D$, if $A_0 < cQ_h - R_0$.

Suppose that $A_0 = cQ_h - R_0$ and $r_1 = r_D$. The bank would not need to borrow reserves. Suppose that it does not borrow reserves (and thus does not lend reserves). It could instead:

(i) borrow reserves from the central bank and lend them in the market or keep them with the central bank. Since $r_M > r_1 = r_D$, this would make the bank worse off.

(ii) borrow reserves in the market and keep them with the central bank. Since $r_1 = r_D$, this would not make the bank better off.

Thus, there is an equilibrium with $r_1 = r_D$, if $A_0 = cQ_h - R_0$.

Finally, suppose that $A_0 > cQ_h - R_0$ and $r_1 = r_D (= 0 < r_M)$. Suppose that the bank keeps all its reserves with the central bank, i.e. is inactive in the market. It could instead lend $A_0 + R_0 - cQ_h$ in the market. Since $r_1 = r_D$, this would not make the bank better off. Thus, there is an equilibrium with $r_1 = r_D$, if $A_0 > cQ_h - R_0$. ■

RESULT 2

Suppose that $A_0 < cQ_h - R_0$ and $r_1 = r_2 = r_D (= 0 < r_M)$. Since $r_1 = r_2 < r_M$, the bank would not borrow from the central bank. It could borrow in the market in $t = 1$ and keep the borrowed reserves with the central bank overnight. Or it could lend reserves in the market in $t = 1$ instead of keeping them with the central bank. But both would not be an equilibrium. Or it could be inactive in the market in $t = 1$. If this was the case, the bank would need to borrow reserves in the market in $t = 2$, if Q was such that $A_0 < cQ - R_0$, e.g. if $Q = Q_h$. This would not be an equilibrium either. Thus, there is no equilibrium with $r_1 = r_2 = r_D$ for all $Q \in [Q_l; Q_h]$, if $A_0 < cQ_h - R_0$.

Suppose that $A_0 = cQ_h - R_0$, and $r_1 = r_2 = r_D$. The bank would not need to borrow reserves. Suppose that it does not borrow reserves and keeps all excess reserves that it has if $Q < Q_h$ with the central bank in $t = 2$. It could instead:

(i) borrow reserves from the central bank (in $t = 1$) and lend them in the market (in $t = 1$ and again in $t = 2$) or keep them with the central bank. Since $r_M > r_1 = r_D$ and $r_M > r_2 = r_D$, this would make the bank worse off.

(ii) borrow reserves in the market and keep them with the central bank. Since $r_1 = r_D$ and $r_2 = r_D$, this would not make the bank better off.

(iii) lend reserves in the market in $t = 2$ (instead of keeping them with the central bank), if $Q < Q_h$. Since $r_2 = r_D$, this would not make the bank better off.

Thus, there is an equilibrium with $r_1 = r_D$ and $r_2 = r_D$, if $A_0 = cQ_h - R_0$.

Finally, suppose that $A_0 > cQ_h - R_0$ and $r_1 = r_2 = r_D (= 0 < r_M)$. Suppose that the bank keeps all its reserves with the central bank. It could instead lend in the market. Since $r_1 = r_2 = r_D$, this would not make the bank better off. Thus, there is an equilibrium with $r_1 = r_2 = r_D$, if $A_0 > cQ_h - R_0$. ■

RESULT 3

Suppose that $A_0 > \max\left\{cQ_h; \frac{M+cQ_l}{2}\right\} - R_0$ and $r_1 = r_M$. As $A_0 + R_0 - cQ_h > 0$, the bank does not need to borrow and could even lend some funds in the market without violating condition (3). Suppose that it does not borrow and it does not lend. Then it would keep as reserves with the central bank $A_0 + R_0$ in $t = 1$ and $A_0 + R_0 - cQ$ in $t = 2$. But because $A_0 + R_0 > \frac{M+cQ_l}{2}$, i.e. $A_0 + R_0 + A_0 + R_0 - cQ_l > M$, it would overfulfil the reserve requirements at least if $Q = Q_l$ so that some of the reserves would be remunerated only at the rate r_D. The bank would thus do better by lending some of the funds in the market as $r_1 = r_M > r_D$. (More precisely, it would set $CI_1 \leq \frac{M+cQ_l}{2} - (A_0 + R_0)$ which is negative in the case considered here.) Thus, there is no equilibrium with $r_1 = r_M$, if $A_0 > \max\left\{cQ_h; \frac{M+cQ_l}{2}\right\} - R_0$.

Suppose that $A_0 = \max\left\{cQ_h; \frac{M+cQ_l}{2}\right\} - R_0$ and $r_1 = r_M$. We need to consider two cases. In case (a), $cQ_h \geq \frac{M+cQ_l}{2}$, i.e. $A_0 + R_0 = cQ_h$. The bank would not need to borrow reserves. Suppose that it does not borrow reserves (and thus does not lend reserves), it could instead borrow reserves from the central bank or in the market and lend them in the market or keep them with the central bank (as minimum or excess reserves). Since $r_M = r_1 > r_D$, this would not make the bank better off. In case (b), $cQ_h < \frac{M+cQ_l}{2}$. If the bank now chooses $CC_1 = CI_1 = 0$, then it holds as reserves $A_0 + R_0$ in $t = 1$ and $A_0 + R_0 - cQ$ in $t = 2$ so that (because $A_0 + R_0 = \frac{M+cQ_l}{2}$) it would not have already over-fulfilled its reserve requirements before $t = 3$ even if $Q = Q_l$. Thus, even if $A_0 + R_0 > cQ_h$ it could not do better than keeping all its reserves with the central bank rather than lending them in the market. This is because it would earn r_M for holding them with the central bank and the same for lending in the market (given that $r_M = r_1$). Thus, there is an equilibrium with $r_M = r_1$, if $A_0 = \max\left\{cQ_h; \frac{M+cQ_l}{2}\right\} - R_0$.

Finally, suppose that $A_0 < \max\left\{cQ_h; \frac{M+cQ_l}{2}\right\} - R_0$ and $r_M = r_1$. We need to consider two cases. In case (a), $cQ_h \geq \frac{M+cQ_l}{2}$, i.e. $A_0 + R_0 < cQ_h$. The bank needs to borrow reserves. Suppose that it borrows them from the central bank and is inactive in the market. Since $r_M = r_1$, borrowing the reserves in the market instead would not make the bank better off. In case (b), $cQ_h < \frac{M+cQ_l}{2}$. If $A_0 + R_0 < cQ_h$. The arguments set out in case (a) apply. If $A_0 + R_0 \geq cQ_h$ and the bank chooses $CC_1 = CI_1 = 0$, then it holds as reserves $A_0 + R_0$ in $t = 1$ and $A_0 + R_0 - cQ$ in $t = 2$ so that (because $A_0 + R_0 < \frac{M+cQ_l}{2}$) it would not have already fulfilled its reserve requirements before $t = 3$ even if $Q = Q_l$. Thus, even if $A_0 + R_0 > cQ_h$, it could not do better than keeping all reserves with the central bank rather than lending them in the market given that it would earn r_M for holding them with the central bank and the same for lending in the market (given that $r_M = r_1$). Thus, there is an equilibrium with $r_M = r_1$, if $A_0 < \max\left\{cQ_h; \frac{M+cQ_l}{2}\right\} - R_0$. ■

RESULT 4

Two cases need to be considered:

(a) $(2 + r_M)(R_0 + A_0) - cQ_l \geq \frac{cQ_h}{1+r_M} + c(Q_h - Q_l)$. This is equivalent to $(1 + r_M)(R_0 + A_0) \geq cQ_h$ so that the bank does not need to borrow. Suppose that it does not borrow and does not lend. It would hold as reserves $R_0 + A_0$ in $t = 1$ and $(1 + r_M)(A_0 + R_0) - cQ$ in $t = 2$, i.e. $(2 + r_M)(R_0 + A_0) - cQ_l$ in total over both periods.

(b) $(2 + r_M)(R_0 + A_0) - cQ_l < \frac{cQ_h}{1+r_M} + c(Q_h - Q_l)$. This is equivalent to $(1 + r_M)(R_0 + A_0) < cQ_h$ so that the bank needs to borrow, at least if $Q = Q_h$. For an equilibrium, this would need to be done from the central bank in $t = 1$. The bank would need to choose (at least) $CC_1 = \frac{cQ_h}{1+r_M} - (R_0 + A_0)$. The banks would then hold as reserves $\frac{cQ_h}{1+r_M}$ in $t = 1$ and $c(Q_h - Q)$ in $t = 2$, i.e. $\frac{cQ_h}{1+r_M} + c(Q_h - Q)$ in total over both periods.

Suppose that $M < \max\left\{(2 + r_M)(R_0 + A_0) - cQ_l; \frac{cQ_h}{1+r_M} + c(Q_h - Q_l)\right\} \equiv M^*$ and $r_1 = r_2 = r_M$. We consider again the two cases from above. In case (a), suppose that the bank does not borrow and does not lend. Because $M < (2 + r_M)(R_0 + A_0) - cQ_l$, the bank would hold excess reserves in $t = 2$, at least if $Q = Q_l$. The bank could do better by lending the funds in the market in $t = 2$ as $r_2 = r_M > r_D$. In case (b), because $M < \frac{cQ_h}{1+r_M} + c(Q_h - Q_l)$, the bank would hold excess reserves in $t = 2$, at least if $Q = Q_l$, if it sets $CC_1 \geq \frac{cQ_h}{1+r_M} - (R_0 + A_0)$. Again, the bank could do better by lending the funds in the market in $t = 2$ as $r_2 = r_M > r_D$. Thus, there is no equilibrium with $r_1 = r_2 = r_M$ for all $Q \in [Q_l; Q_h]$, if $M < M^*$.

Finally suppose that $M \geq \max\left\{(2 + r_M)(R_0 + A_0) - cQ_l; \frac{cQ_h}{1+r_M} + c(Q_h - Q_l)\right\} \equiv M^*$ and $r_1 = r_2 = r_M$. We again consider the two cases from above. In case (a), suppose that the bank does not borrow and does not lend. Because $M \geq (2 + r_M)(R_0 + A_0) - cQ_l$, it would not have already fulfilled its reserve requirements before $t = 3$ even if $Q = Q_l$. It would accordingly earn r_M on all its reserves and would not be better off if it were active (as a lender) in the market. In case (b), because $M \geq \frac{cQ_h}{1+r_M} + c(Q_h - Q_l)$, the bank would not have already fulfilled its reserve requirements before $t = 3$ even if $Q = Q_l$, if it sets $CC_1 = \frac{cQ_h}{1+r_M} + (R_0 + A_0)$. It would accordingly earn r_M on all its reserves and would not be better off if it were active (as a lender) in the market. Thus, there is an equilibrium with $r_1 = r_2 = r_M$, if $M \geq M^*$. ■

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