Know your (holding) limits: CBDC, financial stability and central bank reliance[1]

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Abstract

We assess the impact of a retail central bank digital currency (CBDC) on the balance sheets of banks and the central bank. To do so, we build a constraint optimisation model in which banks react to a system-wide deposit withdrawal by minimising their funding costs subject to their own as well as all other banks' liquidity risk preferences and reserve and collateral holdings. Policy-relevant questions that can be addressed with our model include: For a given CBDC demand and liquidity risk tolerance, what funding mix would banks choose to replace deposit outflows and how would this affect the central bank balance sheet? What proportion of the banking sector would experience an unusually large increase in its reliance on wholesale funding or central bank funding? Which banks have insufficient eligible collateral to obtain the central bank funding they need? We answer these questions for a fictitious digital euro introduction in 2021 using actual balance sheet data from over 2,000 banks and find that a hypothetical €3,000 holding limit would have contained the impact on banks' balance sheets and the Eurosystem balance sheet. Our model suggest that, at that time, concerns about financial stability and monetary policy implementation could have started to arise with CBDC demand exhausting a holding limit of €6,000 or higher.

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1. Introduction

Central banks throughout the world are investigating the potential benefits and risks of introducing a retail central bank digital currency (CBDC). A retail CBDC is a digital form of public money, issued by the central bank and accessible to individuals. Just as banknotes, it can be used as means of payment and store of value, with the benefit of being digital. This feature makes a retail CBDC a close substitute for (overnight) bank deposits. However, a CBDC differs from a bank deposit in that it is a direct liability of the central bank and not of a commercial bank.

Since a retail CBDC is a close substitute for a bank deposit, a successful retail CBDC would likely lead to households shifting part of their funds away from their commercial bank to their central bank. An often-cited financial stability concerns in this context is a potential increase in banks' liquidity risk if banks replace the outflowing stable retail deposits with more flighty wholesale funding or drain their central bank reserves (European Central Bank, 2020; Federal Reserve System, 2022; Bank of England, 2023a). With this in mind, and to facilitate a smooth CBDC introduction, central banks are debating about dissuasive remuneration and quantitative limits to control CBDC holdings (Bindseil and Panetta, 2020; Adalid et al, 2022; Cunliffe, 2023). Others have already implemented such limits, as is the case with the Digital Renminbi, the Digital Bahamian Dollar and the Nigerian eNaira.

What happens on a bank's balance sheet if a customer wants to hold CBDC? If a retail depositor moves €100 from her deposit into CBDC, her bank will need to transfer €100 worth of central bank reserves to the central bank. For the bank, this means a €100 reduction in retail deposits on the liabilities side and a €100 reduction in central bank reserves on the assets side. Should the bank have insufficient reserves, it will need to obtain additional central bank reserves on the interbank market or increase its central bank borrowing.[4] Borrowing can be done secured or unsecured and at different maturities. Each of these options comes at a different cost and has a different impact on banks' liquidity ratios. If banks do not have adequate collateral or their liquidity ratios have reached the regulatory minimum requirement, some adjustment options may not even be feasible.

Based on these adjustment options and constraints, we contribute to the literature by developing a new model to simulate the immediate response of banks to a CBDC-induced, system-wide deposit outflow, which can be applied to different jurisdictions. In our model, each bank chooses the least

[4]We do not explicitly consider the central bank's asset purchase programmes as they are not an active choice of banks but of the central bank. However, the impact of asset purchases on banks is very similar to the impact of central bank lending operations. In both cases, the encumbered or sold assets do not qualify as unencumbered HQLA anymore for the purpose of the LCR. In case of the lending operation, the bank's unencumbered HQLA is reduced slightly more due to the haircut required by the ECB collateral framework. In both cases, reserve holdings of the banking sector increase on aggregate.

expensive balance sheet adjustment that is consistent with its liquidity risk preference, regulation, the availability of reserves and collateral, and market liquidity. It should be noted that we focus on the short-term impact, assuming that bank lending remains constant.[5] The model considers the liquidity coverage ratio, the net stable funding ratio and central bank collateral requirements. Furthermore, each bank's option to tap the interbank market depends not only on its own preferences and asset holdings, but also on other banks' willingness to lend on the interbank market and thus on the deposit outflows, liquidity risk preference and reserve holdings of all other banks and on the total quantity of reserves supplied by the central bank. We are not aware of any paper that has modelled all these constraints at this level of detail.

Moreover, our results contribute to the policy discussion around CBDC holding limits and the demand for central bank reserves. Using proprietary bank-level data from 2,319 euro area banks, we simulate the impact of a hypothetical digital euro introduction in 2021. By investigating at which level of deposit outflows the impact on banks' liquidity risk and funding structure would have been of concern, our results inform the ongoing debate on holding limits. Also, we identify those banks which would have insufficient eligible collateral to obtain the central bank funding they need, and which are therefore of special interest to prudential supervisors. For central bankers, the model's mapping between CBDC uptake and the demand for central bank reserves is of additional relevance.

In our baseline scenario and for the highest CBDC-induced, system-wide deposit outflow compatible with a €3,000 holding limit, we find that the Eurosystem would not have had to provide additional reserves nor would banks have had to change their balance sheets drastically.[6] Specifically, we find that most banks would have relied on their own reserve holdings and that neither the reduction in their central bank reserve holdings nor the increase in wholesale funding reliance would have been extremely large for the bulk of the banking system, as those changes would not have exceeded the 90th percentile of historically observed quarterly changes. Even when considering a bank run scenario, we find that a €3,000 holding limit would have contained liquidity risk.[7] Considering an environment with less central bank reserve supply, and using data from 2019, we find that the central bank may need to provide additional reserves in case of a €3,000 holding limit. This would, however, not have posed a financial stability risk as banks would have had sufficient eligible

[5] We focus on the immediate impact of CBDC, making the conservative but not unrealistic assumption that banks are not able to shed their loans in the short-run. The studies by Whited et al. (2022) and Castrén et al. (2022) take a longer-term perspective, allowing banks to reduce their loans.
[6] In our baseline scenario, we assume that banks are willing to use 50% of their voluntary liquidity buffers, which they hold above the regulatory minimum. For example, for a bank with an LCR of 150% we assume that it would be willing to draw down its LCR to 125%, as the regulatory minimum is 100%. A €3,000 holding limit for the digital euro was suggested by Bindseil (2020) and Bindseil and Panetta (2020).
[7] Of course, households could still transfer their deposits to other banks or withdraw banknotes.

collateral to borrow from the Eurosystem. In contrast, if more than about 30% of banks' overnight household deposits had shifted towards CBDC, a shift which would have been possible but still unlikely with a holding limit of €6,000 in 2021, financial stability and monetary policy implementation concerns could have started to arise.

Related literature

Our paper relates to the emerging literature on the impact of central bank digital currencies on banks. A large part of this literature is theoretical in nature. Brunnermeier and Niepelt (2019) and Fernández-Villaverde et al. (2021) present an "equivalence result": in theory, a deposit outflow to CBDC can take place without macroeconomic consequences if the central bank redirects liquidity back into the banking system under favourable conditions. In practice, one reason such an equivalence result may not hold is due to collateral requirements on central bank lending. Williamson (2022), Burlon et al. (2023), Assenmacher et al. (2021) and Muñoz and Soons (2023) study models in which the central bank's collateral policy affects the economic impact of CBDC. Other reasons why the equivalence result may not hold include bank market power in the deposit market (Andolfatto, 2021; Chiu et al., 2023), a change in bank and government incentives (Niepelt, 2020), external financing frictions (Whited et al., 2022), an improvement in exchange efficiency (Keister and Sanches, 2023).

Focusing on financial stability, the theoretical impact of exchanging retail deposits for central bank funding at favourable rates may even be positive. Kim and Kwon (2023) find that replacing deposits by central bank funding reduces banks' fragility through its general equilibrium impact on banks' asset portfolios. Focusing on the liability side, banks' liquidity risk indeed decreases in our model if deposit outflows are replaced by more stable central bank funding, but only if this central bank funding is not backed by high-quality liquid assets. Therefore, the central bank collateral framework limits the shift of liquidity risk from banks to the central bank in practice.

The application of our model to the euro area banking sector fits in the growing literature on impact assessments of CBDCs, which is still in its early stages. Perhaps the paper closest to ours is Castrén et al. (2022), who use euro area data to consider the possible impact of CBDC on sector-level balance sheets and market prices under different adjustment scenarios, including the central bank redirecting funding back to banks, banks selling assets to the central bank, banks redeeming loans and banks obtaining wholesale funding. We add to the literature in various ways. First, we model the changes at the bank-level rather than at the sector-level. Second, we simultaneously include several different adjustment options in our optimisation problem and let each bank choose its preferred funding mix, rather than considering each option separately. Similar to our work, Whited et al.

(2022) also use bank-level data to quantitatively assess the impact of CBDC in the US. Complementary to our analysis, their focus is on estimating the demand for CBDC and the trade-off for banks between switching to costlier wholesale funding or cutting lending. Also, Gross and Letizia (2023) and Li (2023) complement our analysis by estimating actual CBDC take-up under different assumptions of CBDC design and renumeration. None of these studies consider the constraints imposed on banks by liquidity regulation and collateral requirements.

A few policy institutions have published impact assessments focusing on liquidity regulation. The Bank for International Settlements (2021) considers a stylised model in which the banking system on aggregate holds its Liquidity Coverage Ratio (LCR) constant after deposit outflows by acquiring high-quality liquid assets (HQLAs) using long-term wholesale funding. Gorelova et al. (2022) consider the impact on liquidity ratios of several large Canadian banks in a scenario where retail funding is replaced by wholesale funding with a higher run-off rate. In addition to being more limited in scope than our model, these analyses do not take into account the fact that the acquisition of reserves through long-term wholesale borrowing by one bank results in the loss of reserves at another bank, whose liquidity buffer decreases. As part of its "Digital euro package" the European commission published an impact assessment, part of which relies heavily on the results of an earlier version of our model presented in Adalid et al. (2022).

A related strand of the literature focuses on bank demand for central bank reserves. Afonso et al., 2022; Lopez-Salido and Vissing-Jorgensen, 2023; Bank of England, 2023b study current demand determinants. On top of these, we show that a future CBDC could increase banks' demand for reserves. Abad et al. (2023) also assess the possible impact of CBDC on banks' demand for reserves, using a New Keynesian model, which allows them to draw broader macroeconomic conclusions. In contrast to our model, their study does not account for banks' heterogenous reserve and collateral holdings, which, together with liquidity regulation and collateral requirements, constrain banks' willingness to lend and borrow on the interbank market. Consequently, their model likely underestimates banks' demand for reserves. Besides a sufficient supply of reserves, the availability of eligible collateral is also crucial for a smooth monetary policy implementation. To the best of our knowledge, our paper is the first to assess the impact of CBDC uptake on the scarcity of eligible collateral.

The remainder of the paper is structured as follows. Chapter 2 describes the model and Chapter 3 the data. Chapter 4 presents the simulated impact of the introduction of a digital euro on the Eurosystem's and banks' balance sheets. Chapter 5 considers variations to the sample and model specifications, including a lower initial level of excess reserves, an imperfect interbank market and a bank run scenario. Chapter 6 sets out our conclusions and potential policy implications.

2. The model

We model how each bank optimally responds to a retail deposit outflow by minimising costs and considering their own liquidity, collateral, and reserve constraints, as well as system-wide constraints. In the model, banks can intermediate CBDC demand in three general ways, each with a different impact on its constraints: 1) by using their current central bank reserves or banknotes, 2) by obtaining additional central bank reserves or banknotes on the interbank market, or 3) by increasing central bank borrowing.[8] We do not consider that banks might change their loan portfolio in the medium term in response to a change in funding structure.

Environment and bank funding sources

We consider a model economy with many banks. Each bank re-optimises its balance sheet after an amount ΔD of its retail deposits has been converted to CBDC. The re-optimisation is done with the aim of minimising the adjustment cost, consisting of the change in its cost of funding (ΔCF) and the change in interest income (ΔINC).

A bank can serve its depositors' demand for CBDC by reducing its existing reserve holdings at the central bank, denoted by R, or by obtaining additional central bank liquidity. Additionally, banks can obtain central bank reserves via a range of interbank funding instruments, available on a frictionless interbank market[9]: short-term secured (STS) funding and medium-term secured (MTS) funding (e.g. repos); short-term unsecured (ST) funding (e.g. money market funding); medium-term unsecured (MT) funding (e.g. commercial paper); and long-term debt (LT) funding (e.g. bonds that are either unsecured or secured by assets not considered to be HQLAs, such as certain types of mortgages). ST funding is considered to have a maturity less than one-month, MT funding has a maturity between one and six months, and LT funding has a maturity that exceeds twelve months. These differences in maturity matter for the purpose of the LCR and NSFR. Importantly, each interbank market transaction affects the balance sheet and liquidity ratios of both the borrower and of the lender.[10]

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[8] As elaborated in Adalid et al. (2022), there is a fourth option which we do not consider: the bank could sell assets to obtain reserves. The impact of this option on banks' constraints (collateral, LCR, NSFR) is very similar to that of secured central bank funding.

[9] In Chapter 5 we consider interbank market frictions.

[10] Our model does not preclude banks obtaining liquidity from non-banks. If a bank borrows from a non-bank, reserves are transferred from the bank at which the non-bank holds its deposit to the borrowing bank. This lowers the reserves at the non-bank's bank and increases the reserves at the borrowing bank in exactly the same way as if the bank had borrowed directly from the non-bank's bank. In terms of LCR, the impact for both

The interbank market is a competitive market in the sense that lenders cannot force borrowers to opt for more expensive funding sources if they are not inclined to do so.

There are three types of central bank funding options included in the model, where we assume that the central bank provides as much liquidity as demand requires through its normal market operations. First, short-term ($STSCB$) and long-term ($LTSCB$) central bank funding obtained against HQLA collateral. These options reflect traditional central bank lending operations. Second, long-term central bank funding obtained against non-HQLA central bank eligible collateral ($LTCB$). This option reflects unconventional types of central bank lending operations. Finally, as a last resort, we allow for any residual need for liquidity to be satisfied by a special form of central bank lending which is secured against collateral that is currently not eligible, ($SPCB$). This final funding option is included with the aim of modelling the "residual" need for unconventional monetary policy operations when a CBDC is introduced.[11] It is only available at a penalty rate and is only used if a bank is unable to obtain liquidity otherwise.

Given the different funding options, the change in the cost of funding of bank i equals

$$\Delta CF_i = r^D * \Delta D_i + r^{STS} * \Delta STS_i + r^{MTS} * \Delta MTS_i + r^{ST} * \Delta ST_i + r^{MT} * \Delta MT_i + r^{LT} * \Delta LT_i + r^{STSCB} * \Delta STSCB_i + r^{LTSCB} * \Delta LTSCB_i + r^{L} * \Delta LTCB_i + r^{SP} * \Delta SPCB_i$$

where the interest paid on each source of funding j is denoted by r^j.

Assumption 1: $r^R < r^{STS} < r^{MTS} < r^{ST} < r^{MT} < r^{STSCB} < r^{LT} < r^{LTSCB} < r^{SPCB}$

Assumption 1 specifies the order of relative prices in our model economy, which is assumed to be constant and the same for all banks. Note that we allow for the interest paid to differ between banks. We assume that the deposit facility rate, r^R, provides a floor for interbank market prices and that interbank market funding is cheaper than central bank funding, while secured funding is cheaper than unsecured funding and short-term funding is less expensive than long-term funding.[12] This order of relative prices is what could be expected in an economy without an active unconventional monetary policy encompassing instruments such as targeted longer-term

banks is almost the same. However, the LCR of the non-bank's bank is slightly higher when reserves are lent via the non-bank rather than by the bank itself given that the run-off risk of the non-bank no longer exists.

[11] Instead of lending to banks against collateral that is currently not eligible, the central bank could also provide additional liquidity by purchasing assets from non-bank financial institutions. We do not include central bank asset purchasing programmes as they are not an active choice of the bank but of the central bank.

[12] This order of precedence for pricing is assumed to be independent from the demand for specific funding types for the following reason: when banks reach the lower limit of their liquidity risk tolerance and become reluctant to provide further liquidity on the interbank market, the central bank would supply additional reserves to avoid stress on the interbank market, thereby ensuring that interbank lending prices do not exceed the relevant policy rates.

refinancing operations (TLTROs).[13] The model could easily accommodate bank-specific interest rates for the purpose of studying profitability, in which case the interest rate on deposits relative to other funding option would need to be specified.

The change in the interest income is equal to the change in the return on reserve holdings and interbank lending instruments

$$\Delta INC_i = r^R * \Delta R_i^{TOT} + r^{STS} * \Delta STSL_i + r^{MTS} * \Delta MTSL_i + r^{ST} * \Delta STL_i + r^{MT} * \Delta MTL_i + r^{LT} * \Delta LTL_i,$$

where r^R is the return on central bank reserves, ΔR^{TOT} is the total change in central bank reserves, including reserves exchanged for digital euro (ΔR_i^{OWN}) and those traded on the interbank market (ΔR_i^{IB}), which in turn is equal to the sum of the various types of interbank loans denoted by $STSL, MTSL, STL, MTL, LTL$. Since the rate on reserves provides a floor to market rates, or $r^R < r^{STS}$, it is profitable to lend excess reserves on the interbank market. As wholesale funding is cheaper than central bank funding of similar maturity, individual banks do not resort to the Eurosystem for additional reserves if there is sufficient liquidity on the interbank market.

The banks' optimisation problem

We now specify bank i's re-optimisation problem. For a given outflow of retail deposits, all banks simultaneously choose their balance sheet adjustment, including their role on the interbank market, by solving

$$\min_{R_i^{OWN},STS,MTS,ST,MT,LT,STSCB,LTSCB,LTCB,SPCB,STSL,MTSL,STL,MTL,LTL} (\Delta CF_i - \Delta INC_i),$$

subject to the following constraints, where $c_{j,i}$ denotes the HQLA collateral j of bank i and $c_{CB\,j,i}$ denotes the central bank eligible collateral j of bank i

$$\Delta D_i = \Delta R_i^{OWN} - (\Delta STS_i + \Delta MTS_i + \Delta ST_i + \Delta MT_i + \Delta LT_i + \Delta STCB_i + \Delta LTCB_i + \Delta SPCB_i) \quad (1)$$

$$R + \Delta R_i^{OWN} + \Delta R_i^{IB} \geq 0 \quad (2)$$

$$\sum_i \Delta STSL_i = \sum_i \Delta STS_i \quad (3a)$$

[13] When we allow for TLTROs as the cheapest source of funding, all banks first fully exhaust their TLTRO capacity before resorting to their own reserves. TLTROs would be the most profitable option given their low cost due to the fact that no HQLA collateral needs be pledged, and that there is no negative impact on liquidity risk. In fact, switching from deposit funding to TLTROs may improve bank profitability when the rates paid are below deposit rates.

$$\sum_i \Delta MTSL_i = \sum_i \Delta MTS_i \qquad (3b)$$

$$\sum_i \Delta STL_i = \sum_i \Delta ST_i \qquad (3c)$$

$$\sum_i \Delta MTL_i = \sum_i \Delta MT_i \qquad (3d)$$

$$\sum_i \Delta LTL_i = \sum_i \Delta LT_i \qquad (3e)$$

$$\Delta STS_i + \Delta MTS_i \leq \sum_j \frac{c_{j,i}}{haircut\ c_j} \qquad (4)$$

$$\Delta STSCB_i + \Delta LTSCB_i \leq \sum_j \frac{c_{j,i}}{haircut\ c_j} - (\Delta STS_i + \Delta MTS_i) \qquad (5a)$$

$$\Delta LTCB_i \ \leq \ \sum_j \frac{c_{CB\ j,i}}{haircut\ c_j} - (\Delta STS_i + \Delta MTS_i + \ \Delta STSCB_i + \Delta LTSCB_i) \qquad (5b)$$

$$LCR_i \ \geq 100\% + buffer_i, \qquad (6)$$

$$NSFR_i \ \geq 100\% + buffer_i. \qquad (7)$$

Constraint (1) means that each bank matches its deposit outflow with its own central bank reserves or those newly obtained on the interbank market or from the central bank.[14] Constraint (2) ensures that the bank does not draw down or lend more central bank reserves than it initially owns. Constraints (3a)-(3e) capture the aggregate interbank market liquidity position. Each interbank lending transaction requires a buying bank and selling bank.

Constraints (2)-(3e) together imply that the banking sector as a whole is constrained by the available reserves in the system. To be clear, if a bank uses reserves to meet its costumers' demand for CBDC, irrespective of whether they are its own reserves or those borrowed from another bank on the interbank market, there is a decline in the available reserves in the system.

Constraints (4) – (5b) represent the collateral constraints. Constraint (4) reflects the fact that banks have a limited stock of HQLA collateral suited to obtaining secured market lending. The following unencumbered assets are included in the available stock of HQLAs, at market value and with asset-specific haircuts: government bonds, bonds issued by supra-national institutions, third-country bonds, regional government bonds, corporate bonds, high-quality covered bonds and qualifying

[14] Note that $\Delta D_i, \Delta R < 0$ while $\Delta STS_i, \Delta MTS_i, \Delta ST_i, \Delta MT_i, \Delta LT_i, \Delta STCB_i,\ \Delta LTCB_i, \Delta SPCB_i > 0$.

asset-backed securities (ABS). Constraints (5a)-(5b) determine the type of central bank funding, given that each bank only has a limited stock of HQLA and non-HQLA central bank eligible collateral.

The impact on liquidity risk

Constraints (6) and (7) of the bank's problem ensure that the bank continues to meet its LCR and NSFR regulatory requirements and possibly sustain a bank-specific voluntary liquidity buffer (explained later). These constraints are not only crucial determinants of a bank's preferred funding option, but also of a bank's choice to act as a lender on the interbank market – it does so as long as this does not increase its liquidity risk beyond its preferred level.

The LCR and the NSFR can be impacted in the following two ways for the borrowing bank: (1) if assets are encumbered or sold, they do not qualify as unencumbered HQLAs (decreasing the borrower's LCR) and require more stable funding (decreasing the borrower's NSFR); (2) different forms of funding have different liquidity risks depending on their maturity and on whether or not they are secured, implying different run-off rates; and in the following way for the lending bank: interbank lending lowers reserves and therefore the lender's HQLA (decreasing its LCR) and may increase required stable funding since loans to financial institutions may have a positive RSF factor, while reserves do not. To be clear, if a bank borrows reserves on the interbank market, the liquidity ratios of banks on both sides of the transaction are affected.

The new LCR, after balance-sheet re-optimisation, is calculated as

$$LCR_i = \frac{\widehat{HQLA_i} + \Delta HQLA_i}{E[\widehat{outflow}]_i + \Delta E[outflow]_i}$$

where the variables with a circumflex represent the initial stock of unencumbered $HQLA$s and the initial expected outflow.

Once assets are encumbered, they no longer qualify as unencumbered HQLAs. Reserves are considered to be HQLAs, consequently using or lending reserves on the interbank market also lowers the stock of unencumbered HQLAs. Thus, the change in HQLA is given by

$$\begin{aligned}\Delta HQLA_i \ &= \Delta R_i^{TOT} - HQLA\ adjustment\ due\ to\ bank\ i's\ secured\ borrowing \\ &\quad + HQLA\ adjustment\ due\ to\ bank\ i's\ lending,\end{aligned}$$

$$\begin{aligned}&where\ HQLA\ adjustment\ due\ to\ bank\ i's\ secured\ borrowing \\ &\qquad = \ \Delta STS_i + \Delta MTS_i + \Delta STSCB_i + \Delta LTSCB_i\end{aligned}$$

$$and\ HQLA\ adjustment\ due\ to\ bank\ i's\ lending = \ \Delta STSL_i + \Delta MTSL_i + \alpha\ \Delta LTL_i$$

The first equality uses the assumption that the haircuts imposed by the market are assumed to be the same as those imposed by the central bank's collateral framework, which are the same as the LCR haircut for the assets under consideration. It should be noted that each collateral asset has a different haircut. The second equality reflects the fact that in repo transactions the HQLA value of the lending bank is unaffected while a long term secured loan to a financial institution counts as HQLA with a haircut α (equal to 15% in the euro area).

Once deposits are transformed into CBDC, bank i's expected outflows (1) decrease as lower deposit funding implies a lower expected outflow on those deposits but (2) may also increase depending on the run-off rate of the newly obtained funding instruments, if any. Thus, the change in the expected outflow of bank i is given by

$$\Delta E[outflow]_i = \Delta D_i * runoff\ rate\ D_i + \sum_{f_i=STS,MTS,ST,MT,LT,STSCB,LTSCB,LTCB,SPCB} (\Delta f_i * runoff\ rate\ f_i)$$

The new NSFR, after balance-sheet re-optimisation, is calculated as

$$NSFR_i = \frac{\widehat{ASF_i} + \Delta ASF_i}{\widehat{RSF_i} + \Delta RSF_i}$$

where the variables with a circumflex represent the initial stock of available stable funding (ASF) and the initial stock of required stable funding (RSF).

Bank i's available stable funding is impacted in the following ways: (i) it decreases by the contribution of the withdrawn retail deposits to the initial ASF, and (ii) it increases by the contribution of the newly obtained funding sources. Thus, the change in bank i's available stable funding is given by

$$\Delta ASF_i = \Delta D_i * ASF\ factor\ D_i + \sum_{f_i=STS,MTS,ST,MT,LT,STSCB,LTSCB,LTCB,SPCB} (f_i * ASF\ factor\ f_i)$$

A bank's required stable funding may increase for the borrowing bank given that encumbered assets obtain a RSF factor of 100%, while unencumbered assets have asset-specific RSF factors. The required stable funding may increase for the lending bank given that loans to financial institutions may have a positive RSF factor, while reserves do not. Thus, the change ΔRSF_i is given by:

$$\Delta RSF_i = \sum_j \Delta RSF\ factor_j\ x\ collateral\ j\ of\ bank\ i\ encumbered\ when\ borrowing$$

$$+ \sum_{l_i = STSL, MTSL, STL, MTL, LTL} (l_i * RSF\ factor\ l_i),$$

$$where\ \Delta RSF\ factor_j = RSF\ factor\ unencumbered\ c_{i,j} - RSF\ factor\ encumbered\ c_{i,j}$$

$$and\ the\ collateral\ of\ bank\ i\ encumbered\ when\ borrowing = \frac{1}{haircut\ c_j} x\ encumbered\ c_{i,j}$$

The baseline scenario

Our model is sufficiently general to study a wide range of scenarios. To operationalise our model for our application to the euro area, we narrow down the scenarios under consideration as follows.

First, we assume that each bank experiences a range of outflows of its retail deposits, set as a percentage of its total retail deposits. Thus, in our application, we take no account of possible design features of CBDCs, nor do we use an estimation for the demand for CBDC. Instead, we simulate how banks might respond to different retail deposit outflows. In our application, we focus on retail deposits, given that we consider these to be the most likely form of private money to be converted on demand into digital euro (see Adalid et al., 2022). Further, we assume that each bank would lose the same proportion of its retail deposits. Consequently, those banks holding more deposits would experience a greater depletion of their retail deposits in absolute terms. There are, however, grounds for believing that banks with more digitally savvy customers, smaller individual retail deposits or lower deposit rates might be disproportionately affected. Banks might also raise their deposit rates or improve customer services in response to deposit outflows. While such factors can be included in our model, they fall outside the scope of this paper.

Second, banks face relative, rather than absolute, liquidity risk constraints in our model, reflecting the observed liquidity risk preference heterogeneity in our euro area sample**.** In 2021, LCR and NSFR values in the euro area range between just above the regulatory minimum (102%) to more than six times the regulatory minimum (600%). It is likely that banks with high voluntary liquidity buffers would prefer to maintain relatively high buffers following a CBDC introduction, reflecting persistent heterogeneous liquidity preferences. Thus, rather than assuming that all banks would be willing to reduce their liquidity buffer by the same absolute amount, we consider the following three liquidity risk tolerance scenarios: A) banks and markets have a high liquidity risk tolerance and are willing to use and lend reserves until their liquidity ratios hit the regulatory minimum (sustain 0% of their current voluntary buffers), or B) banks and markets have an intermediate liquidity risk appetite and want to keep half of their currently held bank-specific liquidity buffer above the regulatory minimum (sustain 50% of their current voluntary buffers), or C) banks and markets are extremely risk-averse and are not willing to make any reduction to their current liquidity buffers (sustain 100% of their current voluntary buffers).

We refer to Scenario B as our baseline scenario, where a 50% decrease in a voluntary liquidity buffer coincides with the historical median yearly change to individual banks' regulatory liquidity ratios observed since 2016.

3. Data and descriptive statistics

To showcase our model, we apply it to the euro area banking sector. We use regulatory data on 2,319 euro area banks from the third quarter of 2021 to illustrate how a hypothetical introduction of a digital euro would have impacted the balance sheets of the Eurosystem and of banks. Our sample represents 95% of the euro area banking system in terms of total assets. In Chapter 5, we present results based on data for the third quarter of 2019 to gauge the impact of a macroeconomic environment with lower excess reserves and more available collateral.

There is considerable heterogeneity among euro area banks in terms of their reliance on retail deposit funding, i.e., their exposure to a deposit outflow, and in terms of their accumulation of cash and reserves, i.e., the ease with which they could cope with a deposit outflow without borrowing liquidity. In this regard, we distinguish between significant institutions (SIs), which account for 5% of banks but represent 83% of the total assets in our sample, and less significant institutions (LSIs).[15] SIs are grouped by business models according to an ECB Banking Supervision business model classification.[16] Global systemically important banks (G-SIBs) and universal banks together account for more than half of total assets in our sample. Chart 1 illustrates the relative size of each group in our sample.

[15] LSIs are banks that do not fulfil any of the significance criteria specified in the Single Supervisory Mechanism (SSM) Regulation – significant institutions being those that fulfil at least one such criterion (see e.g. https://www.srb.europa.eu/en/glossary). In practice, the bulk of LSIs are smaller banks whose individual assets do not exceed €30 billion.

[16] Differing from the ECB Banking Supervision classification, and to enhance readability of the charts, we include credit lenders in the retail lenders category and asset managers and custodians in the investment bank category given that we found the impact of digital euro on those types of financial institution to be very similar to banks in the categories concerned. It should be noted that development/promotional lenders are not included in the results in this paper because they are government-owned and are likely to behave differently.

Chart 1

Relative proportion of bank assets in our sample by business model

(share of total assets)

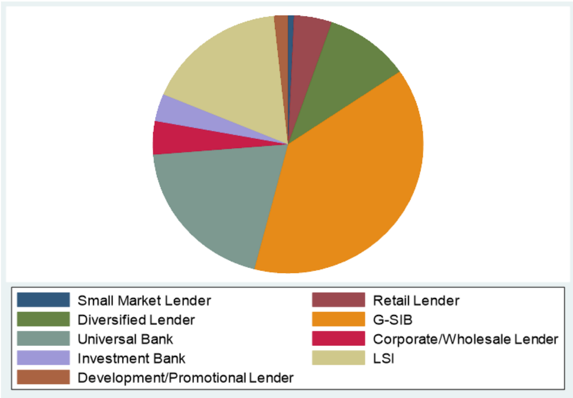


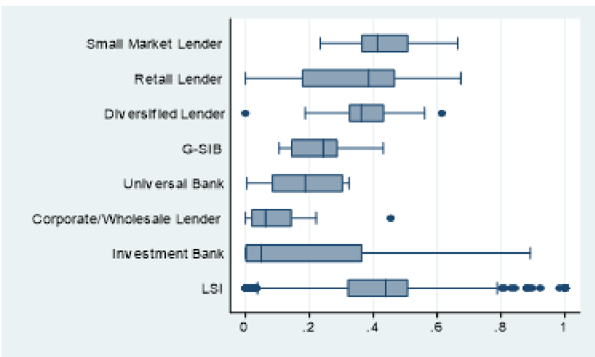
Chart 2 provides a breakdown by business model of banks' reliance on retail deposit funding (panel a) and their accumulation of reserves (panel b). Small market lenders, retail lenders, diversified lenders and LSIs are particularly reliant on retail deposits: half of banks within these business model categories rely on retail deposits for more than one-third of their funding. In contrast, G-SIBs, universal banks, corporate or wholesale lenders, and investment banks are less reliant on retail deposits. Banks' reserves and banknote holdings are also distributed heterogeneously, although the variation between banks is smaller than the variation in the deposits-to-assets ratio. With regard to SIs, the highest median reserve-to-asset ratios are to be found among investment banks, universal banks, small market lenders, wholesale lenders and diversified lenders. LSIs generally hold relatively little reserves and banknotes, given that many are savings banks or cooperative banks. These institutions often organise their liquidity risk management centrally. Their central institutions, which are usually SIs, hold reserves on their behalf.

Chart 2

Banks' disposition and resilience to retail deposit outflows by business model

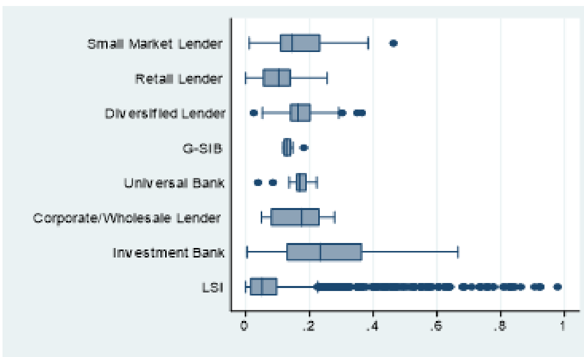
a) Deposits-to-assets ratios for overnight household deposits

(x-axis: deposit-to-asset ratio)



b) Reserves-to-assets ratios

(x-axis: reserves-to-asset ratio)



Notes: In panel b, banknotes are included in reserves.

In Chart 3, information on banks' exposure to deposit outflows and their reserve holdings is combined. We denote the sum of bank i's reserve holdings and banknotes by R_i and its retail deposit funding by D_i. The maximum percent α_i of retail deposit outflows that a bank can accommodate on its own without turning to the interbank market or the Eurosystem equates to

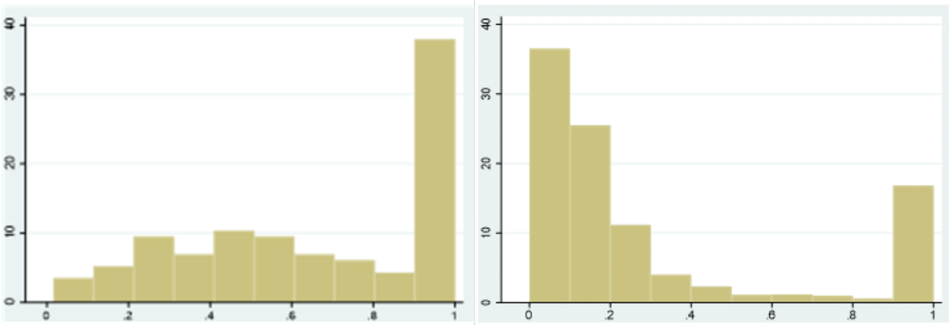
$$\alpha_i = \min(100\% , \frac{R_i}{D_i})$$

Chart 3 presents the distribution of α_i in our sample, split between SIs (panel a) and LSIs (panel b). It shows that many SIs could accommodate an outflow of all their retail deposits. More than 90% of SIs and 40% of LSIs could deal with an outflow of 20% of their retail deposits on their own, whereas the rest would need to resort to the interbank market or the central bank to obtain additional reserves. As indicated above, savings banks and cooperative banks, which make up a large share of LSIs, would naturally resort to their central institution to obtain additional reserves.

Chart 3

Proportion of banks able to fund retail deposit outflows into digital euro on their own

a) Significant institutions	b) Less significant institutions
(x-axis: α% of overnight deposit outflow) (y-axis: percentages of total banks)	(x-axis: α% of overnight deposit outflow) (y-axis: percentages of total banks)



Most banks would not, however, rely solely on their own reserves to accommodate deposit outflows into a digital euro. Rather, banks would obtain additional reserves from the interbank market or from the Eurosystem's regular open market operations. As the choice between the different funding options is not trivial due to interdependencies across banks with liquidity regulation and collateral requirements, we simulate the resulting optimisation problem using our model.

4. Simulation results

We apply our model to quantify the impact of a digital euro introduction on the balance sheets of the central banks and banks for different levels of deposit outflows and three different liquidity risk tolerance scenarios. We determine for each of the liquidity risk tolerance scenarios and levels of deposit outflows the type of interbank funding which banks would choose: short term or long term, secured or unsecured. We also determine when banks would be reluctant to provide further reserves on the interbank market, calling for more liquidity to be supplied by the Eurosystem. With regard to the latter, we also establish whether or not banks would have sufficient currently eligible collateral to obtain such funding for a given level of deposit outflow. Finally, we investigate which banking groups would experience extreme changes in their funding structures, in particular as a result of relying on wholesale and central bank funding, as compared with their historical changes in funding.

For illustrative purposes, we highlight the outflows compatible with a €3,000 holding limit, as suggested by Bindseil (2020) and Bindseil and Panetta (2020) for the case of a digital euro. Multiplying the €3,000 limit by the euro area population of 340 million gives a maximum aggregate outflow of €1.0 trillion, which would be reached if each bank had converted 15% of its retail deposits into digital euros in the third quarter of 2021, as represented by a shaded area in the charts presenting our results. In practice, it is highly unlikely that all euro area residents would always fully exhaust the holding limit; it is also doubtful whether they would all have sufficient savings to do so. In addition, it is likely that residents would not only convert their retail deposits into digital euros but also some of their banknotes. In essence, we would expect less (and probably much less) than 15% of retail deposits to be transformed into digital euro if a €3,000 limit were to be put in place.

4.1 The impact on the Eurosystem balance sheet

We first study when, how much and which type of central bank funding banks would need in order to maintain their preferred liquidity buffers. Wholesale funding is generally cheaper than central bank funding, whether short term or longer term. Consequently, individual banks do not resort to the Eurosystem for additional reserves if there is sufficient liquidity on the interbank market.

Chart 4 shows the composition of the aggregate central bank funding that would be required to ensure that banks would operate within a given liquidity risk tolerance scenario. When deposit outflows exceed 20% in our baseline liquidity risk tolerance Scenario B, or 40% under Scenario A, banks become reluctant to lend on the interbank market. Before this reluctance would lead to rising market prices, the Eurosystem would be likely to provide additional liquidity to banks. Banks would choose between short-term and long-term central bank funding secured by HQLA collateral, long-term central bank funding secured by eligible non-HQLA collateral and central bank funding secured by currently non-eligible collateral. Eligible non-HQLA collateral includes credit claims which are non-marketable assets, and which are therefore not tradable on the interbank market in our model. We use the face value of unsecured eligible collateral as reported by banks to distinguish between central bank funding secured by eligible and non-eligible collateral. This measure disregards the mandatory haircut on eligible non-HQLA collateral and results in an underestimation of the amount of central bank funding secured by currently non-eligible collateral.

We find that banks would primarily use non-HQLA collateral to obtain additional reserves from the Eurosystem. Since we assume that secured interbank funding is cheaper than secured central bank funding, banks would use most of the HQLAs they hold in excess of their assumed preferred voluntary liquidity buffers to obtain secured funding on the interbank market. Should the interbank market start to dry up, there would be few HQLAs left to be used as collateral for central bank funding. Instead, banks would secure their central bank funding using eligible non-HQLA collateral to sustain their preferred liquidity buffers.[17]

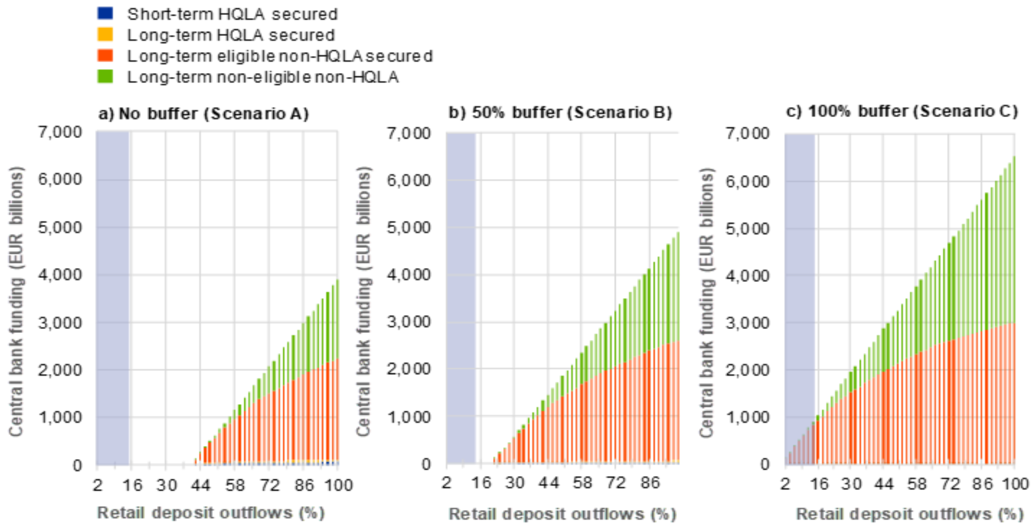
Chart 4 shows that with a €3,000 holding limit, the Eurosystem would not have needed to supply additional reserves under our baseline scenario, Scenario B. In contrast, under Scenario C banks are willing to provide almost no liquidity on the interbank market because they want to keep their liquidity ratios high (panel c). Banks would then require large amounts of central bank funding. In that case, the most extreme outflow with a €3,000 holding limit would result in an increase in the size of the Eurosystem balance sheet of approximately €1.0 trillion. This compares with a Eurosystem balance sheet in the third quarter of 2021 of approximately €8.5 trillion in assets and liabilities. Most banks would, however, have had sufficient eligible collateral to obtain their desired level of funding. We find that, in Scenario C, it was only when outflows exceed 16% that more than 10% of the longer-term central bank funding required would be sought against non-eligible collateral. This assumes that no eligible non-HQLA collateral is traded on the interbank market.[18]

[17] It should be noted that a small amount of HQLA-secured lending would be possible in our simulation even if banks were to hit their LCR constraint given that the LCR denominator decreases when additional retail deposits are withdrawn, making it possible for some HQLAs to be encumbered before the LCR constraint again becomes binding.

[18] Figure A.1 in Appendix A allows for eligible non-HQLA collateral to be traded on the interbank market. Where this is the case, 10% of the longer-term central bank funding required would be sought against non-eligible collateral only if deposit outflows exceeded 70%.

Chart 4

Additional central bank reserves required for an orderly digital euro introduction

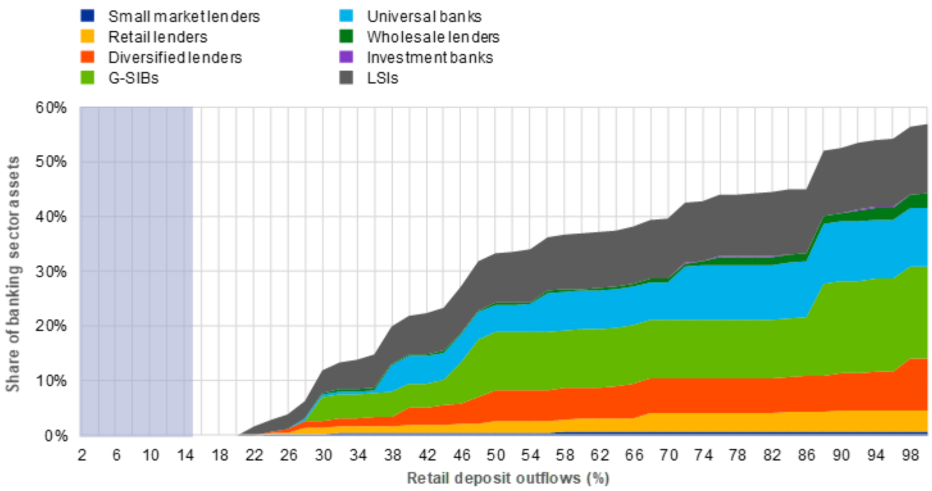


Notes: The shaded area represents the possible share of deposit outflows in the event of a €3,000 holding limit.

We find that, should deposit outflows be unrealistically high, some banks would not have sufficient currently eligible collateral to obtain the reserves required to keep to their preferred liquidity buffers. Chart 5 shows a business model breakdown of the proportion of the banking sector's total assets that are held by banks with insufficient eligible collateral in the third quarter of 2021 to obtain the central bank funding they would have needed to keep half of their voluntary liquidity buffers. In our sample, LSIs would be the first to run out of currently eligible collateral, followed by diversified and retail lenders. Based on our simulations, if outflows exceeded 28% – almost double the most extreme outflow with a €3,000 holding limit – the first G-SIB would have had insufficient collateral to obtain the funding it required.

Chart 5

Share of total banking sector assets of banks with insufficient eligible collateral for central bank funding for a given proportion of retail deposit outflows – Scenario B



Notes: The shaded area represents the possible share of deposit outflows in the event of a €3,000 holding limit.

4.2 The impact on banks' balance sheets

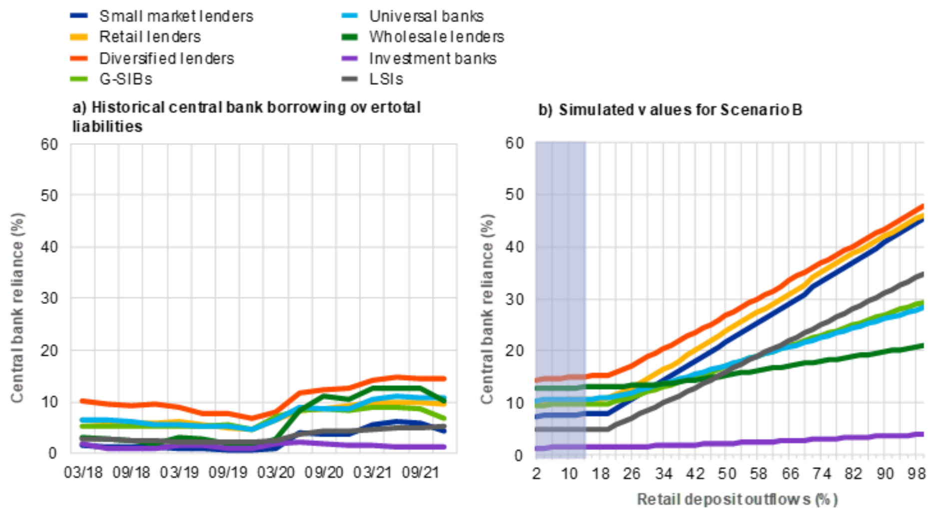
4.2.1 Central bank reliance

We next investigate if and when the substitution of central bank funding for retail deposits would have led to unusually high levels of, or large increases in, banks' central bank reliance. Such changes in central bank reliance would not per se present a risk for the banking sector given that central bank funding is a stable form of funding. Excessive reliance would, however, expose the central bank to counterparty and market risks, and might undermine desirable market dynamics and discipline.

Chart 6 presents the change in the levels of central bank reliance. We find that diversified lenders, small market and retail lenders in particular, but also LSIs, would become the most reliant on the Eurosystem if deposit outflows were much larger than the most extreme outflow with a €3,000 holding limit. Still, the greater central bank reliance simulated for LSIs remains below the central bank reliance observed among diversified lenders in the third quarter of 2021 for outflows less than 50% of retail deposits.

Chart 6

Changes in central bank reliance, aggregated over the different business models

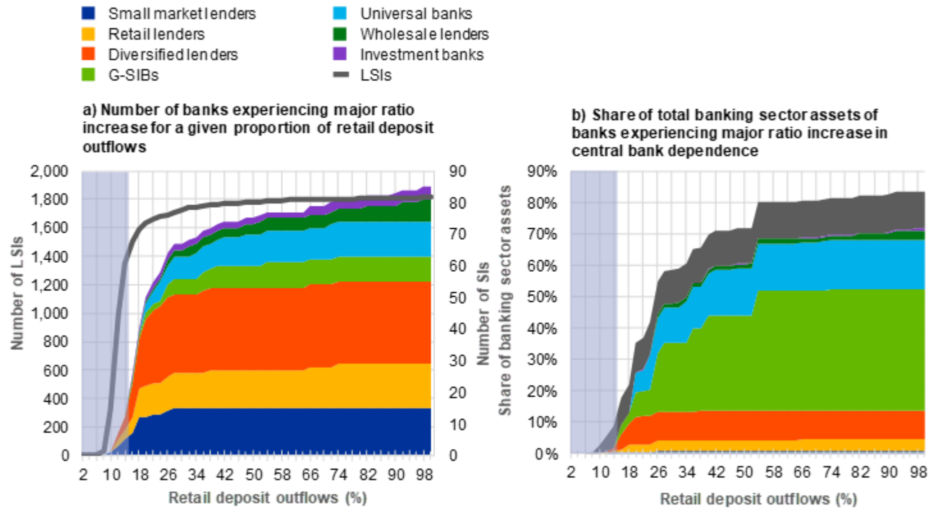


Notes: The shaded area represents the possible outflows in the event of a €3,000 holding limit.

As regards changes in central bank reliance, for illustrative purposes we first consider Scenario C, in which central bank dependence would increase the most with banks maintaining their high voluntary liquidity buffers. Chart 7 shows the number of banks and the percentage of the banking system, in terms of total assets, for which an increase in central bank funding would be exceptionally high as compared with the 90th percentile of quarterly increases in central bank funding of their peers observed since 2016. If banks were unwilling to increase its liquidity risk whatsoever and instead relied on central bank funding, less than 10% of the banking sector would experience an unusually high increase in central bank reliance in the event of the most extreme outflow with a €3,000 holding limit. The vast majority of banks that would experience an unusual increase in central bank reliance are LSIs. It should be noted, however, that LSIs have seen relatively low increases in central bank reliance in the past, hence even small increases in that reliance are considered unusual.

Chart 7

Significant changes in central bank funding ratios under Scenario C for a given proportion of retail deposit outflows



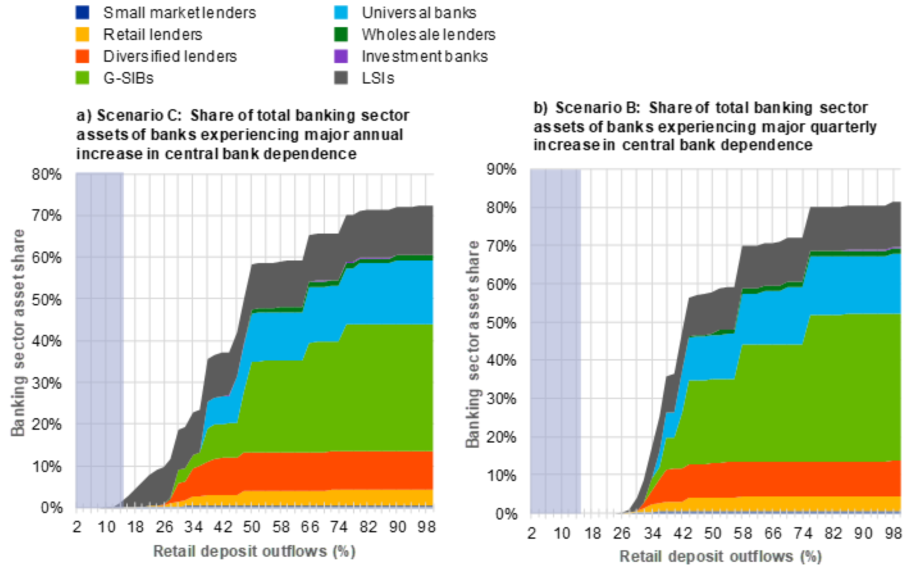
Notes: Major ratio increases are those changes which are above the 90th percentile of quarterly central bank funding ratio increases observed since 2016 for SIs and LSIs respectively. In panel a, the left-axis shows the number of LSIs and the right-axis the number of SIs per business model. The shaded area represents the possible outflows in the event of a €3,000 holding limit.

A slow CBDC introduction taking place over at least a year would render any changes to central bank reliance less extreme. Unsurprisingly, banks have in the past seen larger increases in central bank reliance over a year than over a single quarter. If the digital euro was phased in over a year (Chart 8a), the increase in the central bank funding ratio would only become extreme for more than 10% of the banking system in Scenario C if more than 28% of retail deposits were to be converted into digital euros.

The results presented in Chart 7 are based on Scenario C and thus represent a worst-case scenario in terms central bank dependence. A less extreme outcome is obtained under the baseline scenario, Scenario B, in which banks are willing to reduce their high liquidity buffers by half. As can be seen from Chart 8b, under Scenario B, increases in central bank funding would become more extreme as compared with 90th percentile quarterly ratio changes only if more than 32% of retail deposits were withdrawn. This is due to the fact that banks turn to interbank lending before resorting to central bank funding.

Chart 8

Significant changes in central bank funding ratios for less extreme scenarios



Notes: Major ratio increases are those changes which are above the 90th percentile of yearly (panel a) and quarterly (panel b) central bank funding ratio increases observed since 2016 for SIs and LSIs respectively. The shaded area represents the possible outflows in the event of a €3,000 holding limit.

4.2.2 Wholesale funding reliance

Whether banks choose to act as a borrower or lender on the interbank market depends on their reserves and deposit holdings, as well as on their liquidity preferences. Unsurprisingly, in the simulation interbank market lenders tend to be those banks with a relatively low reliance on retail deposits and with large reserves, such as investment banks and wholesale lenders. On the other hand, G-SIBs and LSIs are the largest absorbers of wholesale funding (which includes liquidity flows from central institutions to affiliated savings or cooperative banks), see Chart A.2 in Appendix A.

We find that the largest share of interbank funding is unsecured with medium-term maturity, such as commercial paper with 3-6-months maturity. Chart 9 shows the aggregated volumes of different types of interbank funding for a range of deposit outflows. Panel a shows the various types of interbank funding opted for by banks in Scenario A, where banks have a relatively high liquidity risk tolerance and use their entire voluntary liquidity buffer above the regulatory minimum. Panel b shows interbank funding choices for our baseline scenario, Scenario B.[19] Banks prefer secured short-term funding given that this is the cheapest type of interbank funding. However, this increases banks' liquidity risk and hence negatively affects their LCRs and NSFRs. We find that the largest share of interbank funding is unsecured debt with a medium-term maturity (such as commercial paper with a maturity of 3 to 6 months), in line with the fact that this is the cheapest source of funding that

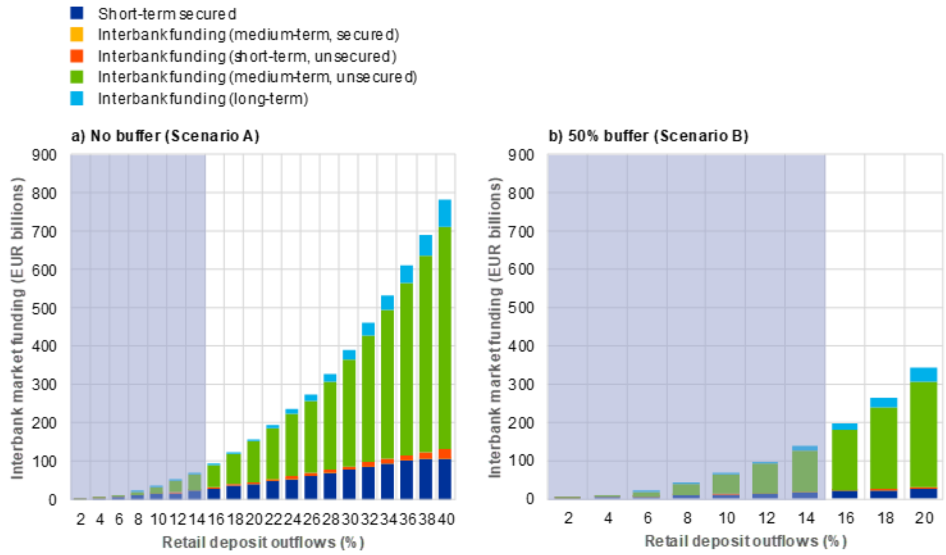
[19] Scenario C is omitted given that there is almost no interbank lending.

does not negatively affect a bank's LCRs in our model. Banks would, however, need to resort to more expensive long-term funding to sustain their NSFR buffers should too many retail deposits, which count towards stable funding, be withdrawn.

Our simulations show that under our baseline scenario, Scenario B, and based on data for the third quarter of 2021, 82% of the most extreme outflow with a €3,000 holding limit would have been replaced, on aggregate, by own reserves (not shown in Chart 9), 14% by medium-term unsecured interbank funding and only 2% by short-term secured funding and 1% by long-term unsecured funding.

Chart 9

Simulated interbank market funding for a given proportion of retail deposit outflows



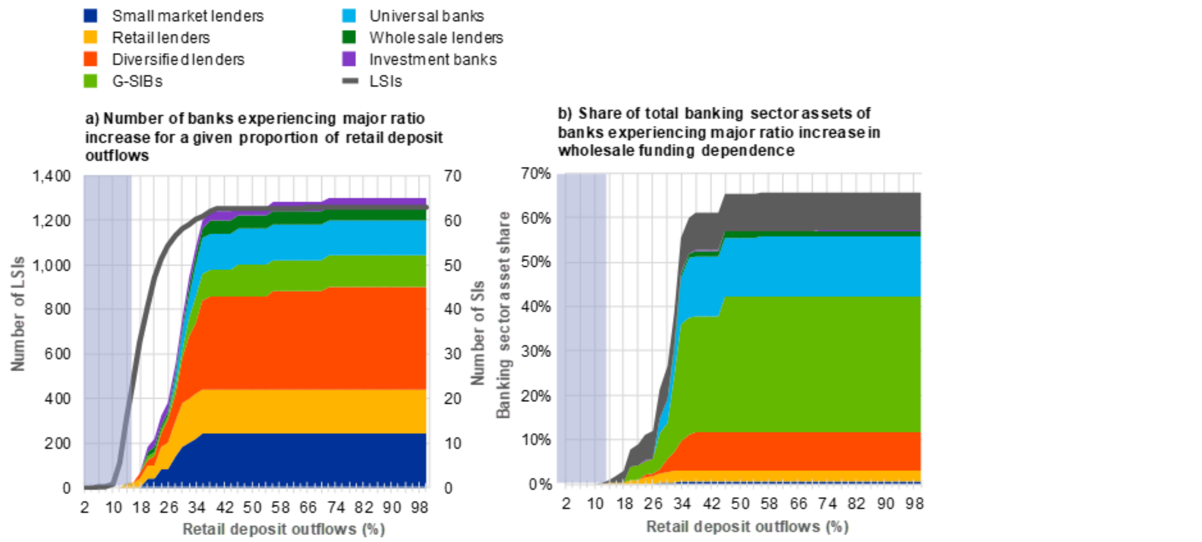
Notes: The data used for this simulation were those for the third quarter of 2021. The shaded area represents the possible outflows in the event of a €3,000 holding limit.

The funding structures of banks that are net borrowers on the interbank market would shift from retail deposits to wholesale funding. Chart 10 shows the number and asset share of banks that would experience exceptionally high increases in their wholesale funding ratio under Scenario A as compared with the 90th percentile of quarterly increases in wholesale funding ratios of their peers observed since 2016.

We find that the number of LSIs with an unusual increase in their wholesale funding ratio would rise sharply if more than 10% of retail deposits would have been withdrawn. Such banks would, however, account for just a small proportion of total banking sector assets. It is only when outflows exceed 20% of retail deposits that a first steep increase would be seen in the proportion of banks, in terms of total banking sector assets, with an unusual increase in their wholesale funding ratio; this is due to the impact of a single G-SIB and of some of the larger retail banks. It is not until deposit outflows exceed 24% of retail deposits, or €1.6 trillion, that banks representing 10% of total banking sector assets would experience a significant increase in their wholesale funding ratios.[20] Given that the bulk of retail deposits would be replaced by medium-term unsecured funding, the short-term liquidity risk would not increase, although banks' funding structures would become less stable over a longer time-horizon. Again, it should be stressed that the increase in liquidity risk which is usually associated with an increase in wholesale funding is constrained by banks' liquidity regulation and risk tolerance.

Chart 10

Significant changes in wholesale funding ratios for a given proportion of retail deposit outflows - Scenario A



Notes: Major ratio increases are those changes which are above the 90th percentile of quarterly wholesale funding ratio increases observed since 2016 for SIs and LSIs respectively. Central bank funding is excluded from the wholesale funding ratio. The shaded area represents the possible outflows in the event of a €3,000 holding limit.

In the baseline scenario, Scenario B, or in the event of a longer digital euro introduction phase, wholesale funding ratio increases would not be a source of concern, even with extremely large deposit outflows. Chart 10 presents an extreme scenario in terms of the impact on wholesale funding for two reasons. First, the ratios are simulated for Scenario A, in which banks use their entire liquidity buffer above the regulatory minimum. It is, however, much more likely that banks would not willingly engage in interbank lending and borrowing to this extent and that the impact on wholesale funding would therefore be lower (while the impact on central bank funding would be higher). Under our baseline scenario, Scenario B, banks could lose more than half of their retail

[20] With lower outflows, deposit funding would be partially substituted by wholesale funding, and wholesale funding ratios would increase. If the interbank market ran out of liquidity, additional deposit outflows would primarily be substituted by central bank funding, although deposit outflows would also free up required reserves, which could then be used to meet the demand for digital euro; this would decrease total assets, while wholesale funding would remain constant. Consequently, wholesale funding ratios would continue to increase slightly even if there was no additional interbank funding.

deposits before banks representing more than 10% of total banking sector assets would experience an extreme increase in their wholesale funding ratios (see panel b of Chart A.3 in Appendix A). Second, the simulated wholesale funding ratio changes are compared with the historical increases over a single quarter. If the simulated increases are compared with the historical increases over one year, the increase in wholesale funding is extreme solely for some LSIs (see Chart A.3, panel a, in Appendix A).

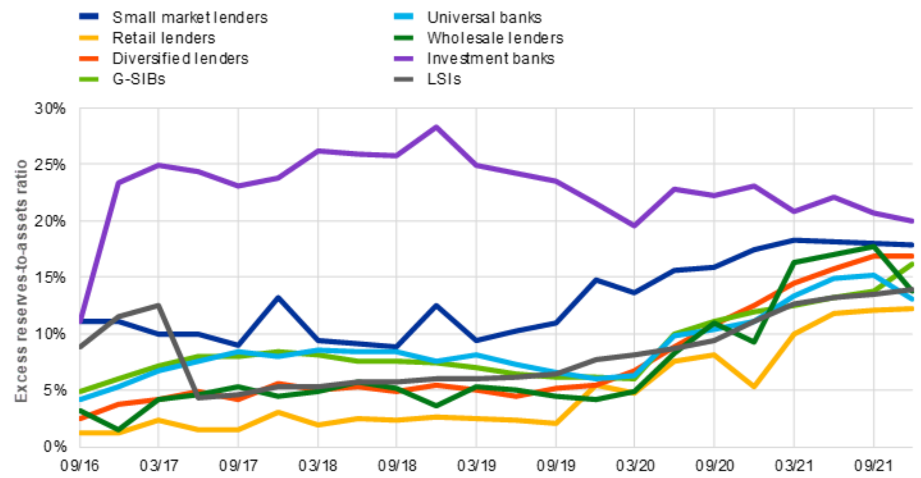
5. Alternative model specifications

5.1 An environment with lower excess reserves

The simulation results presented in the Chapter 4 are based on data for the third quarter of 2021, a high reserve environment. After the start of the pandemic in March 2020, the ratio of central bank reserves to total banking sector assets increased to an exceptionally high level, as shown in Chart 11, which goes hand in hand with lower available collateral.

Chart 11

Historical changes in banks' excess reserves-to-assets ratio



To assess the impact of a digital euro in a lower reserve environment, we repeat our analysis using data for the third quarter of 2019 to reflect that the level of reserves in the banking system might be lower if, and when, a digital euro is introduced. It is impossible to anticipate how each bank's balance sheet would adjust to any future normalisation of reserves or the policies or regulations that would accompany such normalisation. In the third quarter of 2019, the aggregate reserve ratio was around 6%, whereas it was close to 14% in the third quarter of 2021 (see Chart 11). The period selected (the third quarter of 2019) is as far back as we could go due to data availability and to the evolving regulatory environment. Also, the period predated the restarting of the Asset Purchasing Programme (1 November 2019), after which the excess reserve ratio started to increase. It is also after the LCR requirement was fully phased in (1 January 2018), but before the NSFR requirement was phased in. Thus, to facilitate comparison with Chapter 4, we assume in the simulation model that the NSFR constraint is not binding for those banks that did not meet that requirement.[21]

The data for the third quarter of 2019 showed that banks would have required additional central bank reserves even at a lower deposit outflow. Naturally, with lower reserves the banking system could only accommodate a lower proportion of deposit outflows without obtaining additional central bank reserves if the banks were to sustain their preferred liquidity levels. In Chapter 4, we stated that if banks sustain their regulatory minimum liquidity buffers (Scenario A), the banking system could accommodate 40% of deposit outflows without resorting to central bank funding and 20% if they retained half of their current voluntary buffer (Scenario B). The data for the third quarter of 2019 showed that those deposit outflow percentages would have fallen to 20% and 12% respectively. In the third quarter of 2019, a 12% deposit outflow would have equated to €0.7 trillion. Consequently, banks, in 2019, would have required additional reserves from the Eurosystem in our baseline scenario, Scenario B, in the event of the most extreme outflow with a €3,000 holding limit.

While banks held less reserves in the third quarter of 2019, they had also pledged less collateral with the Eurosystem and sold less of their collateral in quantitative easing programmes. Almost all banks had enough eligible collateral to obtain the additional reserves that would have been required for a 15% deposit outflow, the most extreme outflow with a €3,000 holding limit. Chart 15 (in Chapter 6) shows that more than 10% of the banking sector would have required central bank funding secured by currently non-eligible collateral in the third quarter of 2019 only if the outflows had exceeded 38% (and eligible collateral had not been traded on the interbank market).

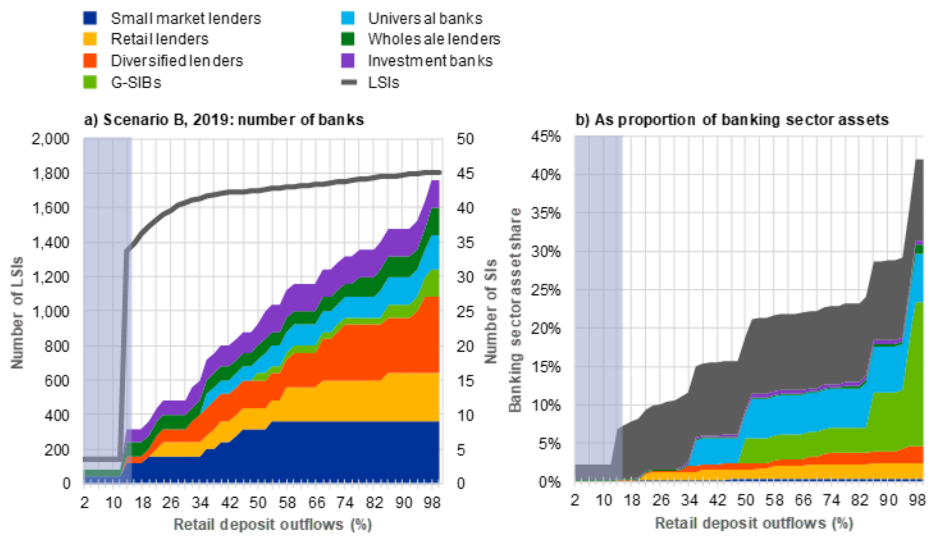
Also based on the data for the third quarter of 2019, the impact on banks' funding structures would have been contained. The increases in the wholesale funding ratios are smaller with lower excess reserves in the system given that there are fewer banks willing, or able, to provide liquidity on the interbank market. The impact on central bank funding reliance would not have been of any concern either when compared with historical values. Although banks would have required central bank funding at a lower deposit outflow, they had a lower level of central bank funding dependence to start with. Applying Scenario B to the 2019 data, only if the outflow exceeded 26% of retail deposits – equivalent to €1.5 trillion and therefore significantly more than the most extreme outflow of €1.0

[21] Due to this assumption, we underestimate the reliance on long-term interbank market and central bank funding relative to short-term funding. As little use is made of long-term interbank market funding (see Figure 8), this assumption is likely to have only a small impact on our results.

trillion with a €3,000 holding limit – would more than 10% of the banking sector have had central bank funding ratios higher than the highest ratio value observed since 2016 (see Chart 12).

Chart 12

Banks with simulated central bank funding ratio higher than their own highest observed ratio since 2016



Notes: In panel a, the left-axis shows the number of LSIs and the right-axis the number of SIs per business model. The shaded area represents the possible outflows in the event of a €3,000 holding limit.

5.2 An interbank market segmented across national borders

It is well documented that most banks predominantly lend to banks located in the same country when economic uncertainty is high, also within the euro area. In Chapter 4, we consider a digital euro introduction with a perfect interbank market, i.e., banks are willing to lend to any other bank in our sample, regardless of where they are established, provided that this does not increase their liquidity risk beyond their preferred levels. In this chapter, we illustrate how our model can be modified to study interbank market frictions, such as when banks are only willing to lend to banks located in the same country.

We find that even in case of interbank market segmentation, under our baseline scenario, Scenario B, the banking sector in all euro area countries could accommodate the most extreme outflow with a €3,000 holding limit without requiring additional central bank reserves. However, there was indeed considerable heterogeneity in the amount of excess reserves and reliance on deposit funding within the national banking sectors in the third quarter of 2021 (see Table A.1 in Appendix A). Banks in Belgium, Ireland, Portugal and Finland were better positioned to accommodate digital euro demand without requiring additional central bank funding as compared with banks in Germany, Greece, Spain and Italy. The banking systems in Belgium, Cyprus and Luxembourg even had sufficient reserves to accommodate the outflow of all retail deposits within their countries without banks breaching their liquidity requirements.

Changes to banks' funding structures and their liquidity risks would also have been moderate if interbank markets had been segmented. Table 2.A summarises the key take-aways, showing that in the event of the worst-case deposit outflow of 15%, the immediate changes to banks' balance sheets would not be extreme for the vast majority of the banking sector. In addition, compared to the case of a frictionless interbank market, there would have been almost no difference in the overall amount of additional reserves banks would on aggregate require to keep half of their voluntary liquidity buffers, as shown in Chart 15.

5.3 A retail bank run scenario

Our model can also be used to study the impact of a withdrawal of retail deposits during a bank run, regardless of whether deposits are withdrawn to hold banknotes or digital euros. To be clear, we do not suggest that a bank run would be caused by the introduction of a CBDC. Rather, our model could be used to study the point at which a sudden and rapid outflow of retail deposits would lead to liquidity risks, regardless of what has caused the outflows. Compared to outflows into banknotes, one advantage of CBDCs is that, in the event of a bank run into CBDC, a holding limit could limit the maximum possible withdrawal of deposits for the purpose of holding CBDC. A second advantage is that a rapid increase in CBDC demand could be observed by the central bank in real-time so that it could provide the necessary liquidity to the system as needed, thus avoiding interbank market stress (see Keister and Monnet, 2022).

In the following, we modify our model to study the case of a bank run. In this alternative model specification, we assume that a bank subject to a run would be unable to obtain reserves from other banks and could only accommodate deposit outflows while it still has excess reserves or eligible collateral. Starting from the model specification used in Chapter 4, we removed the possibility of banks to obtain interbank funding. This means that we assume that no other bank would be willing to lend to a bank experiencing a bank run. We also drop the LCR and NSRF constraints in the constraint optimisation problem given that regulatory buffers are meant to be used when needed. For the sake of illustration, we also include the unrealistic assumption that such banks could not obtain non-HQLA secured central bank funding while they still hold reserves or HQLA collateral. Under these assumptions, the constraint optimisation would simplify to the following bank response during a bank run: a bank would first use all its reserves to satisfy deposit outflows without sustaining its regulatory or voluntary liquidity buffers. Once the bank has fully depleted these, it would obtain the remaining reserves from the Eurosystem, either through normal market operations if it has eligible collateral or via emergency liquidity assistance (ELA). If the bank is unable to obtain reserves to facilitate deposit outflows, it would be illiquid. It should be noted that we consider an extreme scenario in which it is assumed that LSIs would be unable to access any liquidity they might have stored elsewhere, e.g. with their central institution in the case of savings and cooperative banks.

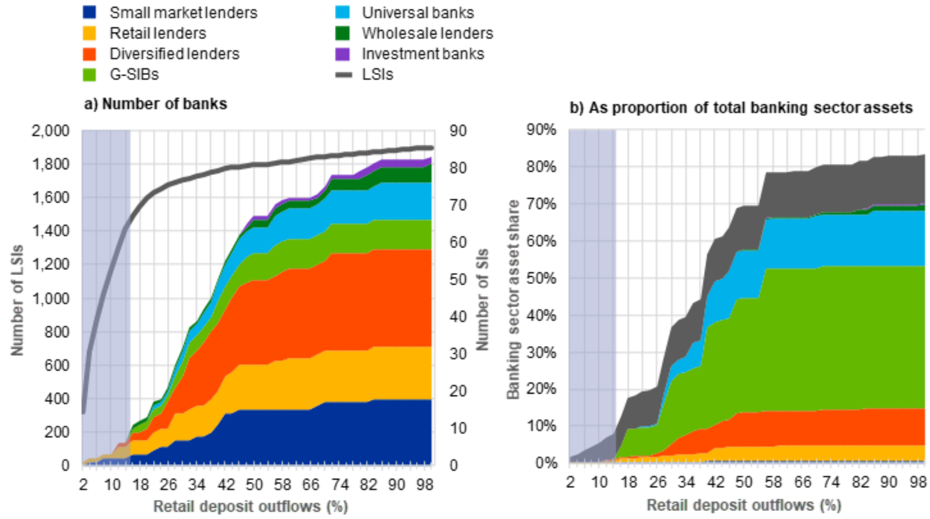
We first analyse the impact of a bank run on banks' liquidity buffers. Liquidity buffers are there to be used during a crisis. Consequently, a breach in liquidity ratios would not be a major concern, but would indicate elevated liquidity risk. Chart 13 shows the number of banks that would breach the LCR or NSFR requirement for a given bank-specific retail deposit outflow in a bank run (panel a), and the proportion of the banking system that they would represent (panel b). During a bank run entailing a fairly low deposit outflow, only relatively small LSIs would breach their liquidity requirements. This reflects the fact that LSIs do not generally hold large reserves directly, but often hold liquidity at a central institution. Only a retail deposit outflow of 16% or more would result in a breach of liquidity requirements for a more significant proportion of the banking system, including three G-SIBs.

While we do not have the depositor-level data that would be needed to determine the maximum deposit outflow into digital euro for each individual bank in the event that all its depositors were to make use of their €3,000 holding limit, a 15% deposit outflow could still serve as a benchmark.[22] Based on this benchmark, we conclude that a €3,000 holding limit would contain liquidity risks stemming from outflows into digital euro for the lion's share of the banking sector. Obviously, retail depositors could still withdraw their deposits by transferring money to another bank account or by obtaining stablecoins or banknotes, as is the case today.

[22] For comparison, the banking sector in Greece, in 2015, and Cyprus, in 2013, experienced a retail deposit outflow around 20%.

Chart 13

Banks breaching at least one liquidity requirement (LCR or NSFR) for a given proportion of deposit outflow

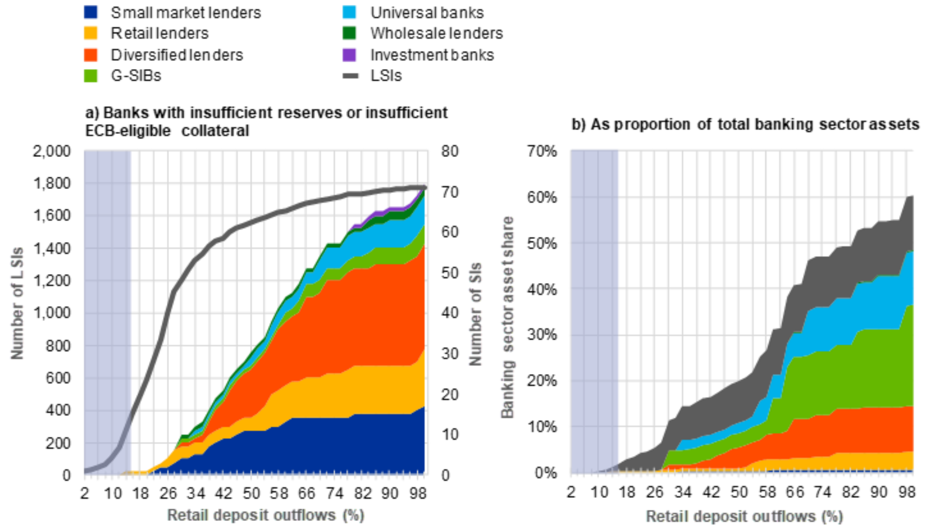


Notes In panel a, the left-axis shows the number of LSIs and the right-axis the number of SIs per business model. The shaded area represents the possible outflows in the event of a €3,000 holding limit.

We next assess the outflows during a bank run that would result in banks needing ELA unless they could obtain reserves from their affiliated central institutions. During a bank run, banks without sufficient reserves and without sufficient eligible collateral to meet deposit withdrawals could fail unless they could secure reserves from an affiliated central institution or obtain ELA from the Eurosystem. Chart 14 shows the number of banks that did not have sufficient reserves in in the third quarter of 2021 to meet a given outflow of retail deposits and, at the same time, did not have sufficient eligible collateral (panel a). Chart 14 also indicates the proportion of total banking sector assets these banks represented (panel b), distinguishing between different business models. Almost no banks would have required ELA during a bank run for bank-specific outflows of less than 15%. Thus, we conclude that a €3,000 holding limit would have made it unlikely that banks would have become illiquid in the event of a bank run into digital euro.

Chart 14

Banks requiring emergency liquidity assistance for a given proportion of deposit outflows



Notes In panel a, the left-axis shows the number of LSIs and the right-axis the number of SIs per business model. The shaded area represents the possible outflows in the event of a €3,000 holding limit.

6. Conclusion

In this paper, we develop a constraint optimisation model to quantitatively study the impact of a CBDC introduction on banks' funding structures and their demand for central bank reserves. The model allows banks to select their preferred balance-sheet adjustments to a deposit outflow based on cost-efficiency and given their own and other banks' liquidity ratios and preferences, reserve constraints and collateral availability. The model can be applied to all jurisdictions with available bank balance sheet data.

Using our model, we simulate the impact of a fictitious digital euro introduction in 2021 using data from more than 2,000 euro area banks. Our results are summarised in Table 2.A, Table 2.B and Chart 15. For most of the euro area banking sector, system-wide deposit outflows of up to 30% of banks' overnight household deposits would have been manageable if banks were willing to use half of their voluntary liquidity buffer which they held above the regulatory minimum. Such outflows would have been possible but still unlikely with a holding limit of € 6,000 at the time. In response to banks' increased demand for reserves, the central bank would have needed to provide around €600 billion of additional reserves, about 93% of which against eligible collateral at the time. These aggregate results hide the fact that the impact varies greatly across bank business models. The banks which are most adversely affected are smaller banks, which tend to depend highly on retail deposits and have relatively low reserve holdings

Our results show that with a €3,000 digital euro holding limit per person, the changes to banks' funding structures and their liquidity risks would have been moderate, and no additional central bank funding would have been needed. This conclusion is consistent with Fabio Panetta's statement of 15 June 2022 to the European Parliament that an issuance of digital euros amounting to a total of between €1.0 to €1.5 trillion, which allows for holdings of around €3,000 to €4,000 per capita or 15% of banks' overnight household deposits, would not have negative effects for the financial system (Panetta, 2022).

Our methodology and results aim to inform the debate on the impact of a CBDC on the balance sheets of banks and the central bank, and the calibration of holding limits. While the results presented are indicative, they clearly depend on the prevailing macroeconomic environment and banks' balance sheets at the time of a CDBC introduction, which are likely to change in the meantime and also in anticipation of such event. This is illustrated when comparing our simulation results using data from 2019 and 2021. While banks started with lower reserve holdings in the former period, this potentially adverse precondition was largely offset by the fact that banks held more unencumbered eligible collateral in the latter period. Re-running our model at the time of a CBDC introduction is therefore required to assess whether the timing and the envisaged holding limits are prudent.

More generally, our results indicate that a rise in bank liquidity risk after the introduction of CBDC is not the most pressing issue when considering the calibration of holding limits or dissuasive design features. Banks' liquidity risk is tightly regulated, limiting their ability to borrow from and lend on the interbank market to accommodate CBDC demand. Rather, the more pressing issues will be banks' increased reliance on the central bank for funding, an intensification of collateral scarcity and a larger central bank balance sheet because banks will need to resort to stable and secured central bank funding as a result of liquidity regulation, at least in the short term. If this is seen as a concern, banks could (be incentivised to) reduce their overall liquidity risk at the time of a CBDC introduction by replacing their existing short-term wholesale funding by unsecured longer-term bond issuance.[23] This would reduce the demand for central bank reserves not only for individual banks, but the whole banking system.

[23] A decrease in short-term wholesale funding decreases the numerator of bank's LCR and an increase in unsecured longer-term funding increases the denominator of their NSFR, without having a negative impact on the LCR denominator.

Table 2.A

Summary – Simulated impact on banks' balance sheets in 2021 of a digital euro introduction

Deposit outflows in Q3-2021 that would have led to banks accounting for more than 10% of the banking system's total assets …	Baseline scenario			Robustness	
	Scenario A (no voluntary buffer)	Scenario B (50% vol. buffer)	Scenario C (100% vol. buffer)	Less excess reserves (and 50% vol. buffers)	Segmented interbank market (and 50% vol. buffers)
…experiencing unusually high quarterly (annual) wholesale funding ratio increases	24% (100%)	28% (100%)	100%	100% (100%)	26% (100%)
…experiencing unusually high quarterly (annual) central bank funding ratio increases	50% (60%)	34% (44%)	16% (28%)	28% (40%)	32% (42%)
…having insufficient ECB-eligible collateral	50%	30%	12%	38%	30%

Table 2.B

Summary – Simulated impact on banks' balance sheets in 2021 of a bank run

Deposit outflows in Q3-2021 that would have led to banks accounting for more than 10% of the banking system's total assets having…	Crisis scenario: no interbank market, use of entire regulatory liquidity buffers
…breached their liquidity requirements	16%
…needed ELA: illiquid and no eligible collateral (the first SI needing ELA)	30% (14%)

Table 3

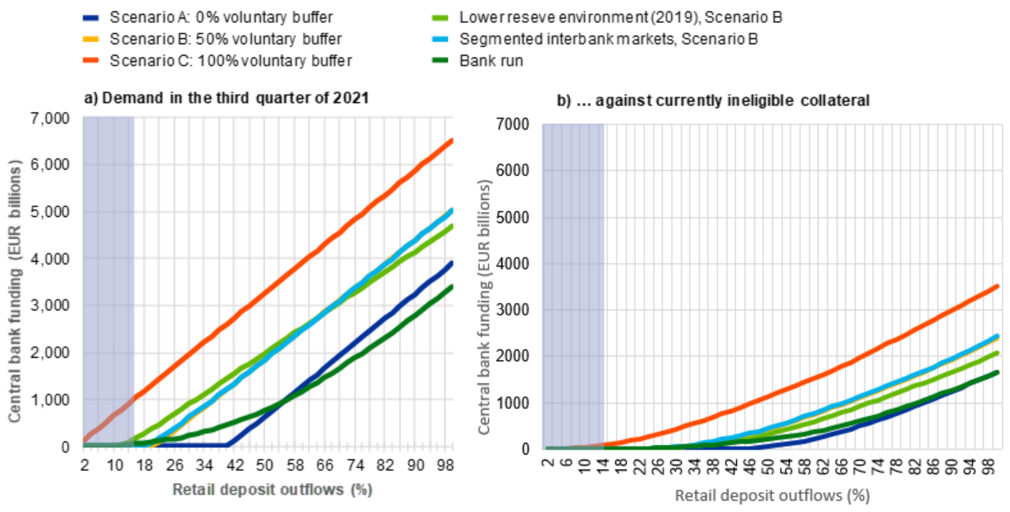
Converting percentage deposit outflows into euro

(EUR billions)

Outflow	1%	5%	10%	15%	20%	25%	30%	35%	40%
Q3, 2021	68.6	343	686	1,029	1,371	1,714	2,057	2,400	2,742
Q3, 2019	58.3	292	583	875	1,166	1,458	1,749	2,041	2,332

Chart 15

Summary – Demand for central bank reserves for a given proportion of retail deposit outflow



Correct right hand chart:

Notes: The shaded area represents the possible outflows in the event of a €3,000 holding limit.

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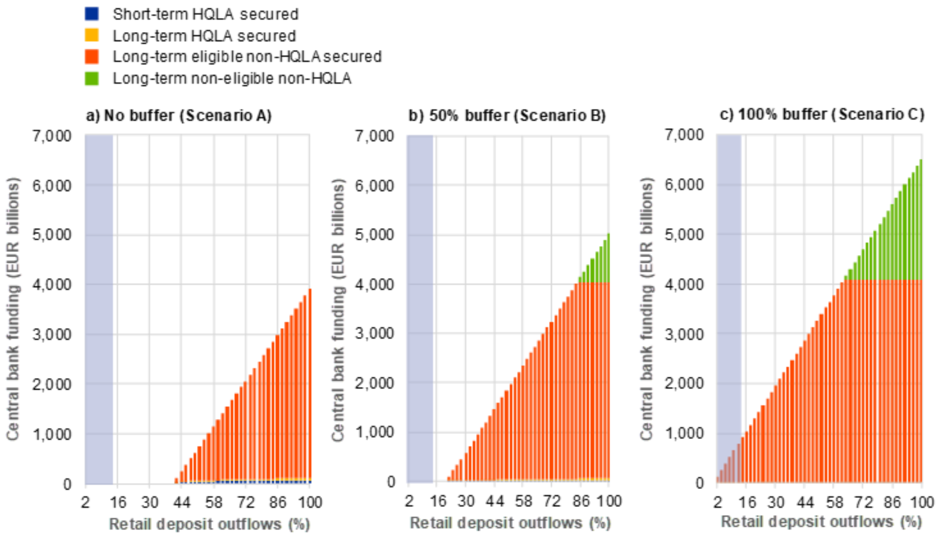
Appendix A: Additional results

Chart A.1

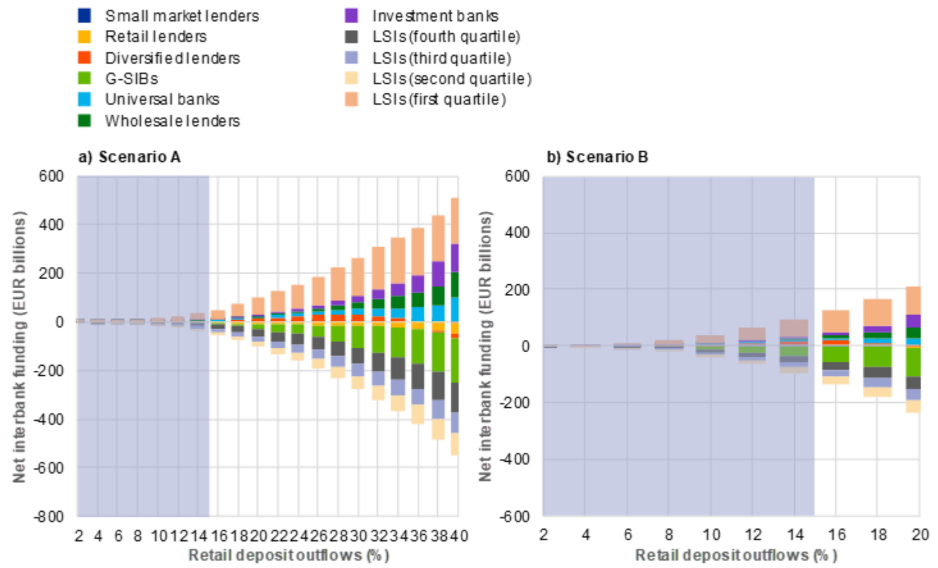
Required central bank funding by type during a digital euro introduction and with a liquid interbank market for eligible non-HQLA collateral



Notes: The shaded area represents the possible share of deposit outflows in the event of a €3,000 holding limit.

Chart A.2

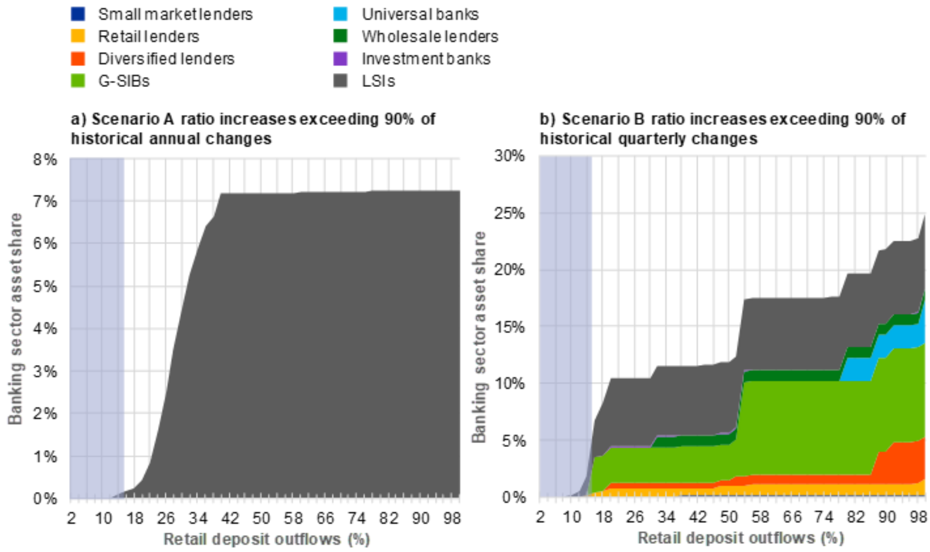
Net interbank market funding position



Notes: The shaded area represents the possible outflows in the event of a €3,000 holding limit.

Chart A.3

Significant changes in wholesale funding ratios in less extreme cases



Notes: The historical increases are those since 2016. The shaded area represents the possible outflows in the event of a €3,000 holding limit. At lower outflows, deposit funding is partially substituted by wholesale funding, and wholesale funding ratios naturally increase. Once the interbank market runs out of liquidity, additional deposit outflows would primarily be substituted by central bank funding. Still, deposit outflows would free up required reserves, which are used to meet the demand for digital euro, decreasing total assets, while wholesale funding remains constant. Consequently, wholesale funding ratios, the ratio of wholesale funding and total assets, continue to increase slightly even if there is no additional interbank funding, and at some point, these increases can become higher than the 90th percentile of historical increases. In panel b, this is for example the case for a G-SIB when deposit outflows exceed 52%, causing a jump in the depicted banking sector asset share.

Table A.1

Country-specific ability to accommodate deposit outflows

Country	Relative size of country's banking sector	Share of retail deposit outflows the country's banking sector can accommodate on its own without additional reserves from the Eurosystem		Required central bank funding secured by non-eligible collateral For: Scenario B; 50% of retail deposit outflows	
		Scenario A	Scenario B	In € billion	As share of outflows
France	29.2%	44%	22%	80	10%
Germany	24.6%	38%	20%	223	29%
Spain	12.2%	34%	20%	40	7%
Italy	10.2%	38%	20%	69	15%
Netherlands	8.7%	44%	22%	13	4%
Austria	3.4%	40%	22%	23	17%
Belgium	2.7%	100%	64%	0	0%
Finland	2.6%	52%	26%	9	12%
Ireland	2.2%	76%	44%	0	0%
Luxembourg	1.1%	100%	46%	1	2%
Greece	1%	30%	18%	17	31%
Portugal	1%	50%	38%	0	0%
Slovakia	0.3%	24%	14%	6	48%
Cyprus	0.2%	100%	56%	0	0%
Estonia	0.2%	50%	26%	2	22%
Slovenia	0.1%	36%	24%	1	16%
Malta	0.1%	48%	32%	0	2%
Latvia	0.1%	50%	38%	1	10%
Lithuania	0.1%	68%	34%	0	3%
Bulgaria	0.1%	52%	28%	0	0%
Hungary	0%	34%	20%	0	8%
Euro area	100%	40%	20%	489	14%