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Central bank digital currencies — design principles and balance sheet implications

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Abstract

This paper sets out three models of central bank digital currency (CBDC) that differ in the sectors that have access to CBDC. It studies sectoral balance sheet dynamics at the point of an initial CBDC introduction, and of an attempted large-scale run out of bank deposits into CBDC. We find that if the introduction of CBDC follows a set of core principles, bank funding is not necessarily reduced, credit and liquidity provision to the private sector need not contract, and the risk of a system-wide run from bank deposits to CBDC is addressed. The core principles are: (i) CBDC pays an adjustable interest rate. (ii) CBDC and reserves are distinct, and not convertible into each other. (iii) No guaranteed, on-demand convertibility of bank deposits into CBDC at commercial banks (and therefore by implication at the central bank). (iv) The central bank issues CBDC only against eligible securities (principally government securities). The final two principles imply that households and firms can freely trade bank deposits against CBDC in a private market, and that the private market can freely obtain additional CBDC from the central bank, at the posted CBDC interest rate and against eligible securities.

Key words: Central bank digital currencies, sectorial balance sheets, monetary systems, financial stability, bank runs.

JEL classification: E42, E44, E52, E58.

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1 Introduction

Central banks are increasingly studying the monetary policy and financial system implications of issuing central bank digital currencies (CBDC).[1] Even though the Bank of England does not currently plan to issue CBDC, it recently published an extensive research agenda on the topic (Bank of England 2016b). This paper is part of that agenda. Its focus is on the sectoral and aggregate balance sheet dimension of CBDC issuance. Because CBDC systems can in principle have very different scope, in terms of the sectors that are allowed to access CBDC, we analyse three possible model variants. In each model CBDC can be viewed as a substitute for commercial bank deposits, and we consider how the introduction of CBDC into the economy may affect the size and composition of the balance sheets of central banks, commercial banks, non-bank financial institutions (NBFIs), and households and firms.

The paper is intended to be a didactic exercise that can be helpful to researchers in the field of CBDC, by providing a clearer understanding of how CBDC might affect balance sheets in practice. Our analysis of the scope for CBDC to displace bank deposits, and/or to affect banks' susceptibility to runs from bank deposits to CBDC, will hopefully be useful in future analyses of the financial stability implications of CBDC. Our paper is also intended to be helpful to policy makers with concerns that the presence of a widely accessible CBDC might be highly disruptive (Constâncio (2017)), and that if it is widely used for transactions it might open the door to rapid bank runs (Broadbent (2016), Callesen (2017)).

Electronic central bank money is not a new concept. It has existed for decades, most ubiquitously as balances (commonly referred to as 'reserves') that are held by commercial banks and other selected financial institutions at the central bank to facilitate electronic settlement in Real Time Gross Settlement (RTGS) systems. CBDC however exhibits several distinct features from reserves. [2] We define CBDC as electronic central bank money that (i) can be accessed more broadly than reserves, (ii) potentially has much greater functionality for retail transactions than cash, (iii) has a separate operational structure to other forms of central bank money, allowing it to potentially serve a different core purpose,[3] and (iv) can be interest bearing, under realistic assumptions paying a rate that would be different to the rate on reserves.[4] This definition allows scope for exploring whether CBDC can be used as a second monetary policy tool, with either a price rule (where the central bank sets the interest rate on CBDC and allows the quantity to vary) or a quantity rule (where the central bank sets the quantity of CBDC supplied and allows the interest rate to vary) possible.

[1] For example, the Sveriges Riksbank have recently published a report examining some of the monetary policy and financial stability consequences of the e-krona model of CBDC, reaching the conclusion that further investigations on this topic are warranted (Sveriges Riksbank 2017). Several other central banks are actively considering the use of distributed ledger technology to provide CBDC for interbank payments. This includes, but is not limited to, the Bank of Canada, the Monetary Authority of Singapore, the European Central Bank and the Bank of Japan.

[2] Bech and Garratt (2017) provide a useful taxonomy of different forms of money. Under this taxonomy, the CBDC in this paper can be classified as 'Settlement Account' money or 'Deposited Currency Account' money, depending of the scale of access, as it is a liability of the central bank.

[3] An alternative definition of CBDC is one where reserves no longer exist separately, having been subsumed into the new CBDC system. In Section 2 we explore why this is unlikely to be desirable from the perspective of the central bank.

[4] The feasibility of this characteristic has been disputed some of the CBDC literature (for example Engert and Fung (2017) and Bordo and Levin (2017)), and as such we provide an exposition of why it is not only feasible but also necessary in Section 2.

We are agnostic as to the technology that underlies CBDC – use of distributed ledger technology (DLT) is not assumed.[5]

The three models of CBDC that we set out in this paper vary in two ways. First, they vary in the sectors that have access to CBDC, from a narrow CBDC where access is limited to commercial banks and NBFIs, a moderate step beyond access allowed to the UK's current RTGS system, to a system where access is also extended to households and non-financial firms. The latter is an economy-wide system similar to the model examined in Barrdear and Kumhof (2016), the 'interest-bearing CBDC' option in Engert and Fung (2017), and also to the 'co-existence with reserves' variant in Meaning et al. (2018). Second, they vary in whether there exist entities that provide deposit facilities that are fully backed by CBDC (as distinct from deposit facilities fully backed by reserves). Economically these entities are narrow banks. The three models together cover a range of plausible CBDC systems that will hopefully prove useful in the analysis of CBDC.

To study the question of how CBDC could affect the size and composition of commercial bank balance sheets we study two sets of scenarios. First, in Sections 4-6, we trace through the changes in assets and liabilities across balance sheets when CBDC is first introduced, and end users shift into CBDC at scale. We do this for all three models. Second, in Section 7, we study an environment where CBDC is already established, and the economy experiences a sudden loss of confidence in the banking sector that results in a large-scale attempt on the part of households and firms to switch their holdings from bank deposits to CBDC. We discuss this generically, without referring back to the three models, as the key insights are common across the models.

For the scenarios of initial CBDC introduction we show that, for all models, if the introduction of CBDC follows a set of reasonable core principles, then the banking sector's two key functions, the provision of credit to borrowers and the provision of liquidity to depositors, are not necessarily curtailed. Some bank deposits may disappear, but, to a first approximation, this can occur without affecting the quantity of aggregate credit or aggregate liquidity. Banks and their customers, through their respective portfolio decisions, control the extent to which depositor switching to CBDC affects the size and composition of bank balance sheets. Banks can continue to play their traditional intermediation role.

For the scenarios of a confidence loss in the banking system, we set out how the likelihood of a run from bank deposits to CBDC can be largely ameliorated through the application of the same core principles.

The core principles are: (i) CBDC pays an adjustable interest rate. (ii) CBDC and reserves are distinct, and not convertible into each other. (iii) No guaranteed, on-demand convertibility of bank deposits into CBDC (via an obligation on commercial banks or the central bank to guarantee convertibility). (iv) The central bank issues CBDC only against eligible securities (principally government securities).

[5] Scorer (2017) sets out why it may not be necessary to use DLT for a CBDC, and also the specific risks and benefits of using DLT for CBDC.

The first core principle is that the interest rate paid on CBDC should be adjustable. This allows the market for CBDC to clear without a need for either large balance sheet adjustments or movements in the general price level.

The second core principle is that CBDC should be distinct from reserves, with the central bank not exchanging reserves for CBDC. As set out in Section 2.2, this addresses the risk of a 'run by the back door', whereby a single bank's commitment to issue CBDC in exchange for bank deposits, together with its commitment to settle interbank payment in reserves, could in the absence of this condition facilitate a rundown in aggregate reserves and deposits when bank customers seek to switch into CBDC. This core principle also enables the central bank to retain control over the quantity of reserves in the financial system, which has traditionally been a key mechanism through which central banks control policy rates.

The third core principle is that commercial banks should never have an obligation to convert deposits into CBDC *on demand*. As set out in Section 7, requiring banks to convert deposits to CBDC on demand opens the door to runs on the aggregate banking system. These runs could be much faster and at larger scale than in the current system, where cash is the only central bank money available to depositors. In such a scenario, there could be substantial operational and political economy barriers to the central bank providing sufficient market-stabilising liquidity support. Such an obligation on banks to guarantee convertibility is therefore highly dangerous.

It is also unnecessary. One frequently cited rationale for this obligation is that it is necessary to ensure parity between bank deposits and other forms of central bank money. However, that parity can be achieved in several other ways, as discussed in Section 2.3.

Relatedly, it has also been put forward that an obligation on banks to always convert deposits to CBDC on demand is critical to maintaining confidence in bank deposits (for example, Meaning et al, (2018)). We challenge this assumption, noting first that greater vulnerability to aggregate bank runs is unlikely to increase confidence in the banking system, and second that the key pillars supporting confidence in banks are strong prudential oversight, maintenance of adequate capital and liquidity buffers, deposit insurance, and commitment to clear interbank payments in reserves at parity (and thereby facilitate payments), rather than the promise to always pay out central bank money to depositors. To see the latter, consider the hypothetical case where banks commit to exchange deposits for CBDC on demand but have little capital or liquid assets, and are not supported by a deposit guarantee. In this case the commitment is not credible and hence cannot be a source of much confidence.

The fourth core principle, which complements the second and third principle, is that the central bank only issues CBDC against eligible assets, principally government securities but with the definition of eligible assets at the central bank's discretion. This conforms to current practice for the issuance of central bank money, and is therefore conservative rather than radical. What would truly be radical, and highly undesirable, is guaranteed issuance against bank deposits, which would amount to a guarantee of automatic unsecured lending to banks.

The results of this paper are a material step forward in understanding how the financial stability risk of CBDC can be managed. Valuable next steps in CBDC research include an improved understanding of the second round effects of introducing CBDC, and developing specific operational designs for implementing the core principles – for example, the design of an efficient mechanism to allow the rate on, or the quantity of, CBDC to adjust in response to supply-demand imbalances. It would also be valuable to explore alternative mechanisms for managing the financial stability risks of CBDC, and their relative costs/benefits to the framework set out in this paper. Such work would benefit from detailed analysis of the magnitude of the potential shifts between deposits and CBDC, including the estimation of the interest semi-elasticities and cross-price elasticities of CBDC and bank deposits. In the sphere of monetary policy, recent work by Meaning et al (2018) could be extended to explore more new and novel policy tools that could potentially become feasible with a CBDC. Analysis of the central bank's own balance sheet risk from issuing CBDC would also be valuable and could build off existing insights from the literature on quantitative easing. Several other research questions are set out in the Bank of England's CBDC Research Agenda (Bank of England, 2016b).

This paper only studies the balance sheet and financial stability aspects of CBDC. It does not attempt to evaluate whether the introduction of CBDC presents a net benefit to the financial system and society. This is still an open question for many central banks, with the answer likely to vary across countries (due to differences in, for example, the service offering of existing payment systems and the prevalence of cash use). A few central banks have taken a decision. In 2015, Ecuador issued a US-dollar denominated national digital currency, while more recently the National Bank of Demark (Gürtler, Nielsen, Rasmussen and Spange (2017)) and the Reserve Bank of Australia (Lowe (2017)) concluded that in their respective economies the potential benefits of introducing a CBDC to households and businesses do not currently outweigh the risks, and therefore they have no plans to introduce one.[6]

The rest of the paper is organised as follows. Section 2 discusses the core principles underlying our specification of all CBDC systems. Section 3 provides an overview of the three models of CBDC, and sets out the simplifying assumptions underlying our stylised balance sheet analysis. Sections 4-6 discuss the mechanics of the initial introduction of CBDC in each of the three models. Section 7 discusses the loss-of-confidence or digital bank run scenario. Section 8 summarises the key insights of the paper.

[6] Engert and Fung (2017) also address this specific question for a CBDC used by the general public and find that some of the motivations for a central bank issuing a CBDC (reducing the effective lower bound on interest rates and reducing financial crime) are not compelling, or could potentially be achieved by other means (such as regulation to increase contestability in retail payments). In contrast, Barrdear and Kumhof (2016) have found, through macroeconomic modelling, that CBDC can convey substantial benefits if issued against government bonds, as it could permanently raise GDP due to reductions in real interest rates, distortionary taxes, and monetary transaction costs.

2 CBDC – Core Principles

2.1 CBDC Pays an Adjustable Interest Rate

A variable, adjustable interest rate on CBDC is important for a number of reasons, some of which will become clearer in the remainder of this section. Broadly, the areas where a variable interest rate plays a key role are monetary policy design, maintenance of financial stability, maintenance of price stability, and maintenance of parity between CBDC and bank deposits.

Price stability and parity are perhaps the most fundamental aspects. Equilibrium in the market for CBDC requires a price to equilibrate demand and supply. Assume that CBDC pays a fixed nominal interest rate of zero, like cash, and that the central bank oversupplies CBDC to the market, perhaps because its estimate of the demand for real CBDC balances is imprecise. We now ask: which price can clear the market by eliminating the oversupply? The first possibility is that CBDC depreciates relative to other forms of money, in other words parity breaks down. This is highly undesirable from the central bank's point of view, but it may be possible to avoid this through the design of the CBDC issuance mechanism, which we will discuss further below. The second possibility is that the exchange rate remains fixed at parity but the general price level clears the market, by reducing the real value of nominal CBDC balances and bringing them in line with the real demand for CBDC. This would directly challenge the anti-inflationary mandate of the central bank, and is therefore also highly undesirable. It is in fact a textbook example of inflationary money printing (electronically). The problem is that if the interest rate on CBDC is not adjustable, there is no third possibility, while an adjustable rate could clear the market by increasing demand for CBDC, without a need for quantitative and therefore balance sheet adjustments, and without a need for parity to break down, or for the price level to adjust. Except perhaps for cases where CBDC is exclusively designed for the narrow purpose of replacing disappearing cash, an adjustable CBDC interest rate is therefore a fundamental requirement for an effective CBDC system.

2.2 Reserves and CBDC are Distinct, and not Convertible into Each Other

2.2.1 Overview

The second core principle is that reserves and CBDC are distinct, and not convertible into each other on demand. This core principle achieves two main objectives.

First, it helps to safeguard financial stability when depositors seek to switch into CBDC in large numbers. Under such circumstances a single bank's willingness to pay out CBDC against deposits can be sufficient to threaten financial stability. This stems from banks' commitment to settle interbank payments in reserves via the RTGS system. When a single bank pays out CBDC against deposits, all non-banks agents can make use of this by transferring deposits to that bank.[7] Upon losing deposits to that bank, other banks must settle the resulting interbank obligations in reserves via the RTGS system. When these reserves are convertible into CBDC on demand at

[7] This is on the condition that they have an account at that bank. However, this is not necessary if the bank chooses to also act as a CBDC exchange. For discussion of the role of a CBDC exchange see Section 5 and the Appendix.

the central bank, the single bank can use its newly acquired reserves to acquire CBDC, in order to then pay out to the depositors that came to it for that purpose. This would lead to a destruction of deposits and facilitate a system-wide, near-instantaneous bank run. Similarly, if reserves and CBDC are not distinct, but instead one and the same, a run via the RTGS system could occur in the same way.

Second, this principle enables reserves and CBDC to have a separate core purpose, in particular CBDC does not have to function as the interbank settlement asset or be bound by the same rules as RTGS. This allows the central bank to operate a second policy instrument, specifically the quantity of or the interest rate on CBDC. This could be used as a tool for monetary policy or for financial stability, while enabling the central bank to retain control over the quantity of reserves in the financial system, which has traditionally been a key mechanism through which central banks control the rate on reserves. Retaining control over reserves allows the central bank to continue to influence the risk-free interest rate in the economy, the key rate for real investment decisions and intertemporal allocation decisions.

This principle also allows scope for a narrow bank to use CBDC to fully back their deposits, again without the risk of fast and potentially large-scale bank runs, which would be present if the narrow bank was connected to the RTGS system, and could use incoming reserves to acquire more CBDC. If the reserves and CBDC systems also use different technological systems, then this might make the overall financial system costlier, but it would also increase the resilience of that system, because CBDC could potentially provide at least a partial back-up service for reserves and bank deposits should the RTGS system fail.

Some papers that study CBDC assume that the market for reserves is subsumed into the new CBDC system. Or, to put this in another way, they assume that CBDC is created via a broadening of access to the reserves system rather than via the introduction of a new form of central bank money (for example, Meaning et al. (2018)). These systems would not allow for this important core principle to be respected, and therefore for the above benefits to be realised.[8] Moreover, broader access to reserves could change the transmission mechanism of monetary policy in unknown ways[9], while at least the transmission mechanism of conventional monetary policy via the policy rate could look very similar to today when reserves and CBDC remain separate.

Other papers argue that – even when CBDC is distinct from reserves – it is not possible for a second policy tool to exist, as arbitrage will bring about convergence between the rates on reserves and CBDC (Engert and Fung (2017), Bordo and Levin (2017)). This conclusion is a direct consequence of the assumption that these two forms of central bank money are essentially identical in the utility they provide to users. If on the other hand, as in our framework, CBDC is used as a retail payment medium, while reserves are used as an interbank settlement medium, this assumption would not hold. Therefore, using instead a set up where reserves and CBDC are

[8] Models that merge CBDC and reserves systems can nevertheless be proxied within our framework (as a theoretical exercise), by relaxing the requirement that CBDC not be paid out for reserves and specifying the special case where the reserves system (RTGS) and the CBDC system are fully interoperable with identical operational structures and purpose.

[9] Meaning et al (forthcoming) discuss some of the potential changes to the monetary policy transmission mechanism, but note that the untested nature of CBDC means that the impact on the monetary policy transmission mechanism is highly uncertain.

distinct, we can show that a new policy instrument is indeed feasible while the traditional policy rate continues to determine the risk-free interest rate, and while at the same time avoiding the above-mentioned financial stability issues that can arise with merged reserves and CBDC.

We will lay out the detailed arguments in subsection 2.2.2 and 2.2.3. Our conclusion is that it is not desirable for CBDC to be the only form of electronic central bank money in the economy.[10]

2.2.2 Arbitrage by Households and Firms

We start by considering the interest rates paid on the different forms of central bank money. The nominal interest rate on cash of course equals zero. The nominal interest rate currently paid on reserves is either equal, or closely related by arbitrage, to the economy's risk-free nominal interest rate, which is an interest rate on a nominally risk-free pure store-of-value asset such as local currency denominated short-dated government bills. The nominal interest rate on CBDC is also risk-free, but this is an interest rate on an asset that functions not only as a store of value but also as a medium of exchange. For a medium of exchange, the return consists of the sum of a financial return and its functionality as a medium of exchange, which in the monetary economics literature is typically referred to as the convenience yield. All else equal, at the margin, the convenience yield is decreasing in the quantity of CBDC and the CBDC demand curve is upward sloping in the interest rate paid on CBDC. Figure 1 illustrates this.

The convenience yield will be especially large when the supply of CBDC is not large relative to bank deposits (a reasonable assumption in our view, and in any event a policy choice), and when CBDC is used as a generally accessible and therefore very useful medium of exchange, where general accessibility refers to the fact that it can be used for transactions not just by banks[11] (like reserves), but also by all other firms and households in the economy. For this case, we adopt the notation cy_{hf}^{cbdc}. Other important properties of the convenience yield are that it will be a function of the stock of CBDC, that is $cy_{hf}^{cbdc} = cy_{hf}^{cbdc}(\text{CBDC})$, that its size is hard to know by the policymaker ex-ante because it depends on many details of the transactions cost technology, and that it could be very volatile, especially during financial crises characterised by rapid changes in the demand for liquidity.

Denoting the risk-free interest rate by rr and the interest rate on CBDC by rc, we have the no-arbitrage condition

$$\text{rr} = \text{rc} + cy_{hf}^{cbdc}(CBDC) \ . \qquad (1)$$

[10] Meaning et al (forthcoming) also find that it is possible to maintain different rates on reserves and CBDC, but they suggest that this is equivalent to a set up with a single form of electronic central bank money that pays one rate to banks and another to non-banks. By contrast we would argue that monies (or more generally assets) that pay different interest rates should not be classified as a single form of money. Furthermore, the conclusion of Meaning et al. (forthcoming) relies on the two assumptions that the central bank commits to converting reserves to CBDC on demand at parity, and that there is little-to-no difference in the services offered by reserves and CBDC. We have set out above why both assumptions are problematic.

[11] And, potentially, a small set of other financial firms such as central counterparties and payment service providers.

Different assumptions about the design of a CBDC system can now be discussed against the background of this condition. The assumption of Barrdear and Kumhof (2016), henceforth BK, is that CBDC is a third form of central bank money, and is therefore distinct, including in the interest rate paid on it, from reserves. This is also the assumption of this paper. The alternative definition, henceforth ALT, is that CBDC represents expanded access to reserves.

The BK assumption under a CBDC price rule is that policy controls both rr, via the market for reserves, and rc, via the market for CBDC. In this world, optimising agents can approach the central bank and exchange eligible securities for CBDC to adjust their holdings of CBDC until $cy_{hf}^{cbdc}(\text{CBDC})$ is consistent with the difference rr – rc, which is set by the central bank. The BK assumption under a CBDC quantity rule is that policy controls both rr and the quantity of CBDC, and that the interest rate on CBDC, rc, is determined by the market, and adjusts to satisfy the arbitrage condition. In both cases, the central bank exploits the fact that the introduction of CBDC makes it possible to control a second policy instrument. The central bank uses this to control both the risk-free real interest rate and either the price or the quantity of an important new form of money.

In ALT, it is instead assumed that the authorities surrender the benefits of a second policy instrument, by mixing the markets for reserves and CBDC. It is typically also assumed that the authorities choose to control the interest rate on, rather than the quantity of, this money. Specifically, reinterpreting rc now as the interest rate on the combined reserves-CBDC money rather than on stand-alone CBDC, the authorities control only rc, which is likely to be very similar to the rc of a BK system because the marginal user, who determines the convenience yield, is in both cases a retail user, that is a household or firm. Crucially, this means that the authorities do not control rr, the risk-free interest rate. But this immediately raises a number of questions.

First, why would the authorities accept the previously discussed financial stability risks?

Second, why would the authorities give up control over a second policy instrument when there is no necessity to do so, and knowing that (as shown in BK) there is at least a chance that this second instrument could make a substantial contribution to stabilizing the economy?

Third, if the authorities had to choose between controlling rr and rc, why would they choose rc? If they control rc, which now equals the rate on both reserves and CBDC, then rr, the risk-free interest rate, will be determined by the magnitude of the convenience yield, $cy_{hf}^{cbdc}(\text{CBDC})$. We have discussed above why the size of this yield is hard to know ex-ante and probably at times very volatile, properties that rr would inherit. But rr, the risk-free interest rate on a pure store-of-value asset, is the key interest rate for all real investment and intertemporal allocation decisions. We conjecture that the authorities would not want to leave such a critical rate to be determined by the markets on the basis of a highly uncertain convenience yield.

A related objection to choosing rc as the only tool of monetary policy is that in any future world the central bank's core mandate would presumably remain the control of inflation. Policy

controls inflation through its effect on aggregate demand. The primary tool for that must be rr, not rc. But if the authorities wanted to continue controlling rr, they would have to do so through the market for reserves, as today. And that in turn requires that the market for reserves be separate from the market for CBDC. The maintained assumption here is of course that the convenience yield in the market for reserves is close to zero, or in any event much smaller than the convenience yield in the much larger market for a retail payment medium.

Matters would be more problematic with a quantity rule for combined reserves-CBDC. Here the authorities would control the quantity of CBDC in Equations (1), but they would not control cy_{hf}^{cbdc}(CBDC) , because that depends not only on money supply but also on money demand, and they would not control any interest rate.

We can also use the no-arbitrage condition (1) to study the argument that arbitrage would eliminate any difference between the interest rates on reserves, rr, and on CBDC, rc. In our framework, rr is in turn closely related by arbitrage to the risk-free interest rate, or the rate on short-term government debt. Assume now that rc = rr. The problem with this assumption is that it requires cy_{hf}^{cbdc}(CBDC) = 0, meaning CBDC would have to reach a satiation point. We can assess the likelihood of this point being reached by considering the situation with bank deposits. Taking the deposit rate[12] to be rd, major economies are typically very far from rd = rr, and this is at levels of bank deposits that are already large relative to GDP. By analogy, expanding CBDC so that rc = rr, even approximately, would therefore probably require an extremely large issuance of CBDC. This would raise two major questions. First, what assets would the central bank buy to back such an enormous issuance? And second, with so much liquidity in the economy from CBDC alone, why would there still be any need for bank deposits and bank loans (which are the main way to create bank deposits); in other words, does this not run the risk of driving banks out of business? These are very reasonable questions, and they lead us to conclude that the central bank would probably like to issue only a moderate quantity of CBDC. And in that case the convenience yield will clearly be of a similar order of magnitude as the convenience yield on bank deposits, which is typically sizeable, on the order of percentage points rather than basis points. It is therefore not likely that arbitrage would eliminate differences between the interest rates on reserves and on CBDC in a BK-style CBDC system. Of course, in an ALT-style CBDC system it would eliminate those differences by assumption, because reserves and CBDC would be indistinguishable in their functionality, but we have pointed out above why such a system may be undesirable.

2.2.3 Arbitrage by Banks

Our analysis up to this point, much of which is contained in equation (1), has centred on the role of non-bank users of CBDC, because they are the agents that determine, in conjunction with central bank policy rules, the interest rate on and quantity of CBDC. The reason is that they are the agents that absorb the marginal unit of CBDC, and that therefore determine its convenience yield, which, given the policy rate, in turn determines the CBDC interest rate. But this analysis

[12] We are referring here to the marginal funding cost to banks, considering that any expansion in bank balance sheets will generally require a more or less proportional increase in both retail and wholesale liabilities, irrespective of the initial funding cost of any balance sheet expansion. The reason is that depositors will generally diversify their portfolios across different types of bank liabilities once they have received the initial new deposit.

is not complete without also considering the role of banks in the CBDC market. We turn to this next. This analysis contains two additional insights.

First, banks will not tend to hold much CBDC. Banks face the same rr and cy_{hf}^{cbdc}(CBDC) as households and firms, because the risk-free interest rate is common to all agents in the economy, while the convenience yield in the CBDC market is determined by the marginal holder at the aggregate level. That marginal holder will be households or firms, who derive substantial benefits from holding a retail medium of exchange, while banks' marginal benefit from holding CBDC over reserves or gilts is likely to be very small by comparison. This means that banks would likely not hold any substantial quantity of CBDC because the opportunity cost would be too high. Formally, and denoting the convenience yield of CBDC to banks by cy_{b}^{cbdc} and the quantity of CBDC held by banks by $CBDC_b$, this represents a corner solution in banks' portfolio problem:

$$\text{rr} > \text{rc} + cy_{b}^{cbdc}(CBDC_b). \qquad (2)$$

When a customer wants to buy CBDC from a bank as a service, the bank can still offer that service if it chooses to do so, but it would do this by purchasing CBDC at the time it is requested by customers. Therefore, for settlement purposes, commercial banks will prefer reserves to CBDC, and away from the zero lower bound (ZLB) such reserves are supplied by the central bank on demand, while at the ZLB they are not in short supply. Banks will only keep as much CBDC on their balance sheet as they consider necessary to satisfy customer requests for CBDC. If customers satisfied their demand for CBDC exclusively in a CBDC market rather than via banks, we would have $CBDC_b = 0$. It should be noted that the corner solution in (2) is analogous to banks' decision on holding physical cash, which is also minimized to the point where it is sufficient to service customer requests.

Second, arbitrage by banks will not cause rr and rc to converge in a world where reserves and CBDC are distinct. Banks cannot "borrow CBDC" at the rate rc and invest it in reserves at the rate rr. CBDC is an outside asset, and banks can acquire this asset like any other security, but they pay for it by creating deposits, which pay the interest rate on deposits. On the other hand, households and firms choose between deposits and CBDC to meet their demand for liquidity.[13] Denoting the rate on deposits by rd, the convenience yield on deposits as cy_{hf}^{dep}, and the spread that compensates deposit holders for the credit risk of holding deposits at commercial banks by s, we have the no-arbitrage condition

$$\text{rd} = \text{rc} + cy_{hf}^{cbdc}(CBDC) - cy_{hf}^{dep}(DEP) + \text{s} = \text{rr} - cy_{hf}^{dep}(DEP) + \text{s}. \qquad (3)$$

The marginal holders of CBDC, households or firms, will therefore be indifferent between deposits and CBDC at the prevailing interest rates and endogenous stocks of these two types of money. They will sell CBDC to banks only if the resulting deposit carries a rate at or above the going deposit rate. The CBDC rate can therefore only affect the equilibrium deposit rate by (3), in other words through the competitive elimination of arbitrage possibilities, but the CBDC rate

[13] Consumers can also hold cash to meet their liquidity needs. This is abstracted from here as it simplifies the argument without affecting the results.

is otherwise not a rate that banks themselves pay on any of their liabilities. And (3) clearly shows that, due to the presence of the convenience yields, rr and rc would in general not be equal to each other in a no-arbitrage equilibrium.[14]

Summarising Section 2.2, when CBDC is distinct from reserves, the result is the elimination of a potentially important source of risk for runs on the banking system, the prevention of a source of potentially costly fluctuations in the risk-free interest rate, and the availability of a second policy instrument for the central bank, either the interest rate on or the quantity of CBDC. The ability to use reserves and CBDC as separate policy tools arises from the central bank being the sole provider of these two distinct forms of money, which are not perfect substitutes for each other or for the other main source of money in the economy – bank deposits. We are not taking a stand on whether this second policy tool should be used for monetary policy or for financial stability purposes, but we emphasise that a second tool is available to be used.

2.3 No Guaranteed, On-Demand Convertibility of Bank Deposits into CBDC

The literature on CBDC sometimes suggests (e.g. Meaning et al. (2018)) that depositors, meaning households, firms and NBFIs, should always be able to convert deposits into CBDC on demand; that is, banks should have an obligation to convert deposits into CBDC at any time and at any quantity. We find that, as a mandatory feature of CBDC, this is both dangerous and unnecessary.[15]

Why is it dangerous? The key consideration is the credibility of the obligation. The banking sector may be able to meet the obligation when the net flows into CBDC and out of deposits are small and slow-moving. However, credibility also relies on being able to meet the obligation in times of stress. This means that the guarantee must cover situations where demand for CBDC is so great that the banking sector has run out of CBDC held on its own balance sheet, so that banks can no longer obtain CBDC from each other. In this situation of exceptionally strong demand for CBDC, the banking sector is also unable to obtain CBDC from the non-bank sector because the assumption is that in this situation that sector as a whole wants more CBDC, not less. Banks would need to sell or repo eligible assets to the central bank to gain CBDC, with the central bank possibly having to expand the list of eligible collateral, or even to dispense with collateral requirements altogether in large-scale unsecured lending. The credibility of the obligation therefore turns on the central bank's commitment to be the lender of last resort, potentially taking an unprecedented risk onto its balance sheet given the potential size of the liquidity requirements. That is, the guarantee of banks to always stand ready to convert deposits to CBDC must ultimately be supported by a guarantee from the central bank.

Another way of stating this is that the central bank must commit to accept, in an emergency, bank deposits in exchange for CBDC. This commitment of course opens the door wide to runs

[14] Engert and Fung (2017) set out an arbitrage strategy for banks that is similar except that it (i) abstracts from the convenience yields on CBDC and bank deposits, and (ii) assumes that banks are able to borrow CBDC in the market at the CBDC interest rate, rather than at the going interest rate on bank deposits, which is what the lenders would receive in exchange for their CBDC. Under these assumptions, they find that the rr-rc spread would, other things equal, reduce to zero.

[15] Indeed, this is not even a mandatory feature for banknotes in the UK. While it is the historical norm that banks pay out cash on demand, there is no formal legal obligation to do so.

from bank deposits into electronic central bank money, which could conceivably be near-instantaneous and of an unprecedented scale, given that it is a run from the banking system as a whole rather than a run from one bank to another. Reflecting this, the scale of the liquidity support that the banking sector may need to request from the central bank would be an order of magnitude larger than in a traditional bank run. [16]

A complementary central bank action would be to lower the rate on CBDC (relative to deposits), to discourage switching. In a panic, rates on CBDC would likely need to be substantially negative to materially stem the outflow of deposits, and negative rates of this magnitude may face political economy barriers. There is also a risk that even substantially negative rates would not be an effective disincentive to hold CBDC in a situation of widespread market panic.

By contrast, consider the situation where banks are not obligated to provide CBDC on demand for deposits. In this case non-banks can nevertheless freely obtain CBDC against bank deposits from other non-banks. We emphasize this: ruling out an obligation on banks to convert deposits into CBDC does not imply that households or firms cannot exchange deposits against CBDC in a private market. Participants in this market that hold eligible assets can furthermore freely obtain additional CBDC from the central bank. What is ruled out is only guaranteed convertibility at commercial banks, and therefore at the central bank. This type of convertibility however does not affect the *aggregate* quantity of bank deposits at all, it only changes their owners. More generally, by definition, there cannot be a run on the aggregate banking system when that run is driven by deposit withdrawals from one bank that end up being deposited in another bank. This is true both for our current banking system and for a CBDC system that rules out a guarantee of convertibility of deposits (and reserves) into CBDC. It is therefore a guarantee of unlimited convertibility that would make a CBDC system fundamentally different from, and more dangerous than, our current system.

There can still be one form of *aggregate* bank run even in a world where convertibility between deposits and CBDC is ruled out, namely a run from bank deposits into cash, but this is as feasible with CBDC as without. Furthermore, it is less likely than a run from deposits to deposits, because the time requirements and expenses associated with physical conversion into cash are much greater than those of digital conversions.

Runs *within* the banking system, where customers move their deposits electronically from one bank to another bank, are also possible in a world where convertibility between deposits and CBDC is ruled out, but again this is as feasible with CBDC as without. The effects of CBDC on the risk of within-system deposits-to-deposits runs, deposits-to-cash runs, and other risks to financial stability are an important area for further research, but there is no a priori reason to think that CBDC would make such runs larger or more likely. In fact, in a CBDC system it may become easier to resolve troubled institutions quickly and without the risk of contagion, which can remove a major reason for depositors to run in the first place (for further comments on this,

[16] It is not problematic if banks provide CBDC for deposits at their *discretion*. For example, it might be the case that banks find it optimal to choose to offer some products that are convertible on demand for CBDC. These liabilities would presumably have liquidity ratios that reflect this characteristic. Banks could also choose to convert regular deposits to CBDC when it suited them, by becoming a seller (against bank deposits) in an economy-wide market for CBDC that is open to banks and non-banks alike.

see Section 7). In this paper we mainly focus on runs out of the aggregate banking sector into CBDC, because that type of run is genuinely new to CBDC, and conceivable if the CBDC system were to be badly designed. Also, of course, the potential scale and scope of this type of run is – by definition – multiple times as large as a run on an individual bank.

Why is guaranteed deposits-to-CBDC convertibility unnecessary? The argument for a guarantee of convertibility of bank deposits into CBDC often seems to be that convertibility is necessary to maintain a 1:1 exchange rate (parity) between bank deposits and central bank money. This is not compelling. Indeed, parity between bank deposits and CBDC can be maintained as long as: (i) The central bank allows the adjustment of the interest rate on CBDC (under a CBDC quantity rule) or of the quantity of CBDC via exchanges of non-deposit eligible assets against CBDC (under a CBDC price rule) such that private sector agents expect the parity condition to hold. That is, the central bank consistently and credibly acts to match the quantities of CBDC demanded and supplied at the targeted quantities or prices. (ii) There is a functioning and liquid market for CBDC eligible securities. (iii) There is at least one private sector agent (such as a bank or other financial institution) that can accept/issue a payment from bank deposits and is active in both the market for CBDC and in the market for CBDC eligible securities.
Condition (i) is self-explanatory. Conditions (ii) and (iii) allow for agents to take advantage of any arbitrage opportunity in this market, thus driving deviations from parity between CBDC and bank deposits to zero.[17] Under these conditions, a plausible outcome would be a large and liquid private market in which households and firms can trade bank deposits against CBDC among themselves, with a few participating agents having access to stocks of eligible securities that can unlock additional CBDC from the central bank. Reliance on this market, together with the presence of at least one agent capable of trading on any arbitrage opportunities, as outlined above, would therefore ensure parity of bank deposits with the national currency as effectively, and with fewer risks, than reliance on their guaranteed convertibility into central bank money at banks.

As for parity between bank deposits and other forms of central bank money, parity between cash and reserves is maintained by the central bank freely exchanging reserves for cash, while parity between reserves and bank deposits is maintained by commercial banks' requirement to settle interbank deposit flows in reserves at parity. Thus, there is parity between bank deposits and all forms of central bank money, and notably, this does not require the central bank to offer guaranteed convertibility, either directly or via an obligation on commercial banks, of bank deposits against CBDC, reserves or cash. It is also notable that the deposits-CBDC-reserves parity does not require that consumers be able to exchange bank deposits for cash on demand. Convertibility of bank deposits into cash, by definition, does of course support parity. However in modern economies, where electronic payments dominate, it is the commitment by banks to settle interbank electronic transfers in reserves that anchors bank deposits to the national currency. This observation is particularly relevant for proposals for CBDC that are motivated by

[17] Say CBDC is trading at an exchange rate of 1-x to deposits, for x>0. Then a financial institution can lock in a riskless profit, by taking 1 unit of deposit inflow from a customer, buying 1 unit worth of gilts in the market, immediately selling the gilt to the central bank for 1 unit of CBDC, delivering 1-x of CBDC to the customer, and keeping x CBDC as riskless profit. Arbitrage will drive x to zero. Note that it is the central bank's commitment to pay 1 unit of CBDC for a gilt worth 1 unit of 'deposit-money' – that is, central bank's use of a parity exchange rate in its operations – that allows this strategy to work.

a desire to address declining cash use and/or to accelerate the demise of cash (see Sveriges Riksbank (2017) and Bordo and Levin (2017), respectively).

There are several other ways in which a CBDC system could be set up to limit the conversion of deposits to CBDC with a view to preventing a run, for example by capping the amount of deposits that banks are obliged to convert to CBDC over a set period, or limiting the quantity of CBDC that can be held in any one CBDC account. However, such limits run the risk of not maintaining parity even during normal times. Moreover, as set out in Gürtler, Nielsen, Rasmussen and Spange (2017), a cap on holdings of CBDC would limit the number or value of transactions that could be made, potentially compromising the effectiveness of CBDC as a payment system. Relating this to financial stability, Callesen (2017) argues that if the cap is high enough to allow CBDC to be useful for transaction purposes it will also be too high to contain the risk of bank runs. This is why we elect to express our core principle as banks having no obligation to provide CBDC for deposits at all. Banks are free to exchange CBDC for deposits, or not, at their discretion. This is an attractive approach as it allows banks to determine for themselves how to manage the risks they face, while – in concert with the other core principles – providing assurance that the risk of an aggregate run out of the banking sector has been addressed.

2.4 The Central Bank Issues CBDC Only Against Eligible Securities

The fourth core principle is that the central bank only exchanges CBDC for eligible securities of its choosing, such as government securities. It does not exchange it for reserves, as argued in Section 2.2, and it also does not exchange it for bank deposits, as argued in Section 2.3. This core principle allows the central bank to manage the risk to its own balance sheet from issuing CBDC, just as it does for reserves and cash. More importantly, these issuance arrangements can mostly eliminate the risk of an aggregate run out of the banking sector, either runs that become possible via a subset of banks when CBDC and reserves are exchangeable, or the generalised runs on the banking system that become possible via the totality of banks when CBDC and bank deposits are exchangeable on demand.

We now set out how CBDC could be supplied from a policy rule perspective. A quantity rule fixes the quantity of the respective central bank money and allows its interest rate to adjust. A price rule fixes the interest rate on the respective central bank money and allows its quantity to adjust. We will use the terms price rule and interest rate rule interchangeably.

Reserves are currently supplied using a combined quantity and price rule in many major economies. Specifically, under Quantitative Easing the central bank purchases a set amount of financial assets in exchange for reserves while setting the interest rate at a near-zero level. Under conventional policy, a price rule is used whereby the central bank sets the interest rate on reserves and supplies the quantity of reserves demanded at that price.

Physical cash (banknotes) is currently supplied under an implicit price rule, with central banks typically providing as many notes as demanded at a fixed interest rate of 0 per cent.

CBDC can be supplied under either a quantity rule or a price rule. Under a *quantity rule for CBDC*, the central bank does not issue additional CBDC in response to an increase in demand, instead allowing the interest rate on CBDC to adjust downwards until the market clears. Under a *price rule for CBDC*, the central bank sets the interest rate on CBDC and allows the private sector to determine its quantity. The central bank does so by freely issuing (or withdrawing) CBDC to the private sector on demand, but only against eligible assets. Under such a rule the issuance arrangements for CBDC are critical.

Eligible assets in our illustration consist only of gilts. A private-sector agent who wishes to switch his bank deposits to CBDC must first acquire gilts in exchange for deposits, in order to then offer the gilts to the central bank in exchange for CBDC, or alternatively the agent must find a counterparty that obtains CBDC from the central bank in exchange for gilts, and is willing to trade that CBDC against the agent's deposits. With these transactions, so long as the gilts are not acquired from the banking sector, the deposits do not leave the aggregate banking system, they are simply transferred to the seller of the gilts. As a result, bank funding cannot, in aggregate, be "lost" when the private sector acquires additional CBDC. The key to this result is that the central bank will not accept bank deposits (or more generally bank IOUs) in exchange for CBDC, in other words it will not fund commercial banks directly. This forces agents to first exchange their deposits for assets that are not bank liabilities, namely gilts, and the counterpart of increases in CBDC holdings is decreases in gilt holdings, not in deposits.

It may be the case that the non-bank supplier of the gilts does not wish to retain the additional liquidity gained when it sold gilts in exchange for deposits, but instead uses the deposits to purchase a different asset. So long as banks do not choose to sell their own assets for these deposits, aggregate bank funding will not be reduced.

If the source of the gilts is from the banking sector, then banks' aggregate balance sheet contracts, however as discussed in the sections that follow, it does so without, to a first approximation, immediately affecting the quantity of credit or of liquidity in the economy. Moreover, if banks are not obligated to provide CBDC for deposits (as recommended in Section 2.3), then banks cannot be forcibly compelled to use their own holding of gilts to supply CBDC for deposits in the first place.

3 Summary of CBDC Models and Assumptions

3.1 The Three Models of CBDC Access

The three models of CBDC that we consider in this paper differ in the sectors that have access to CBDC, from narrow CBDC where access is limited to banks and NBFIs, to a system where direct access is also extended to households and non-financial firms (hereafter simply firms), and finally to a system where households and firms have indirect access to CBDC, through entities that provide deposit facilities that are fully backed by CBDC (that is, narrow banks that

provide an indirect version of CBDC). These models are summarised below, with Figure 2 providing an overview, and with more detailed descriptions provided in Sections 4-6.

> Financial Institutions Access (Model FI): CBDC access is limited to banks and NBFIs.[18] CBDC can then be thought of as being similar to, but in important respects different from, the reserve assets currently used within the Bank of England's RTGS system, with the differences being due to broader access and a different functionality and core purpose.[19],[20] Banks and NBFIs can interact directly with the central bank to buy/sell CBDC in exchange for eligible securities. For this model, it is assumed that there are no institutions that provide an asset to households and firms that is fully backed by central bank money, even though this may be technically feasible, as indeed it is technically feasible today.

We chose to examine this level of access to CBDC as it is a clean boundary that is sufficiently beyond the current status quo for UK electronic central bank money – and the likely status quo after the completion of the current RTGS renewal project (see Bank of England (2017b)) – – to pose interesting questions on what impact it could have on the financial system and the real economy and what new policy tools it may allow.

> Economy-wide Access (Model EW): Alongside banks and NBFIs, households and firms also have access to CBDC. CBDC can therefore serve as money for all agents in the economy. Access does not imply that the central bank provides retail services to all holders of CBDC. In Model EW, only banks and NBFIs can interact directly with the central bank to buy/sell CBDC, while households and firms must use a CBDC Exchange to buy/sell CBDC in exchange for deposits. An alternative where households and firms can directly trade CBDC with the central bank is however also feasible, and of course households and firms can always trade among themselves to buy/sell CBDC. A CBDC Exchange may be a new standalone entity, or operated by a bank or NBFI, but for clarity of exposition we treat CBDC Exchanges as separate entities in our illustration of Model EW. Additional add-on services (such as a user interface to transact in CBDC) could also be provided by third parties.

This model permits us to study how banks would be affected if households and firms could choose between using electronic commercial bank money and electronic central bank money. Broad access CBDC is also studied in Barrdear and Kumhof (2016), Engert and Fung (2017), Sveriges Riksbank (2017) and Meaning et al (2018), although all differ in their exact specification.

[18] If a distributed ledger is used, this could be described as only banks and NBFIs having an address on the CBDC ledger.

[19] The Bank of England's RTGS infrastructure is designed to facilitate the settlement of electronic sterling transfers. In the UK, banks and a few other types financial institutions (such as central counterparties) can hold accounts in RTGS for holding reserves or settling net obligations. Since mid-2017, non-bank payment service providers have also been able to apply to hold settlement accounts in the RTGS system; the first non-bank payment service providers are expected to join RTGS during 2018. For further information on the purpose and operation of RTGS, the difference between reserve and settlement accounts in RTGS and conditions for the provision of settlement accounts see Bank of England (2018) and Bank of England (2017a).

[20] CBDC could have a range of purposes – such as providing an alternative retail payment system and/or a second policy tool. Under the definition in this paper, its purpose specifically excludes it serving as a real time gross settlement system in competition with reserves.

Financial Institutions Plus CBDC-Backed Narrow Bank Access (Model FI+): CBDC access is limited to banks and NBFIs. Within the NBFI sector there is at least one financial institution that acts as a narrow bank, providing a financial asset to households and firms that is fully backed by CBDC but that does not extend credit. That is, they provide households and firms with an asset that has the risk profile of central bank money, rather than a risk profile linked to the financial institution and of its borrowers. Holders of this asset can transact amongst themselves in this narrow bank money (termed indirect CBDC, or iCBDC).[21] We denote the institutions that provide this service as indirect CBDC Providers (iCBDCPs). These iCBDCPs do not need access to reserves and to RTGS to operate. Therefore, for simplicity, in our illustration we assume that they do not hold reserve accounts. This is not important for our results, however, as our core principles address risks both when iCBDCPs have reserve accounts and when they do not.

Including this model allows us to study the differences between direct and indirect access to CBDC by households and firms.

The FI+ model is a material a step beyond what is technically possible under a system with only cash and reserves. In the absence of CBDC, a narrow bank fully backed by cash is unlikely to be a profitable going concern. Given the non-interest-bearing nature of cash and its storage cost, the narrow bank would need to charge a negative interest rate or a fee to cover costs. With this pricing it may fail to attract users, particularly if commercial banks are covered by a deposit guarantee and/or offer 'free if in credit' current accounts (which is the status quo in the UK).[22] Using reserves to fully back narrow bank deposits is problematic for other reasons. A reserve-backed narrow bank must by definition have access to reserves and RTGS. By virtue of this access, when a customer withdraws deposits from a commercial bank to place at the narrow bank the transaction will be settled over RTGS with the commercial bank's reserve account debited and the narrow bank's reserve account credited (assuming no offsetting transaction). This allows consumers a near frictionless and unlimited shift between commercial bank deposits and the central-bank-money-backed asset. This would in turn allow runs on commercial banks 'by the back door' that are faster and larger than what is possible at present, making the existence of reserve-backed narrow banks prohibitively risky to the financial system. The introduction of a CBDC that is separate from the interbank settlement asset – i.e. reserves – introduces the possibility of an asset that is backed by electronic central bank money without the concomitant risks to financial stability described above.

In this context, it is important to note that under current UK regulations, a narrow bank that is fully backed by CBDC might not automatically be eligible to be a member of RTGS and/or have access to a reserve account at the central bank. This is because it would have to be decided whether its activity, which does not include the granting of credit, satisfies the definition of the regulated activity of 'deposit taking' under the *Financial Services and Markets Act 2000 (Regulated Activities) Order 2001 (RAO).* Similarly, a narrow bank does not meet the definition

[21] The existence of multiple providers of iCBDC need not impair its use as a means of exchange to the extent that the iCBDC systems are interoperable.

[22] Narrow banks would be more viable at times when the rate on commercial deposits is materially negative. In this unusual situation households and firms may still prefer to simply hold cash, especially if the narrow bank had few economies of scale in storing cash.

of 'credit institution' at the European Union level as set out in Article 8, Directive 2013/36/EU (CRD), in conjunction with Article 4.1(1), Regulation (EU) No 575/2013 (CRR); s 55A FSMA and the RAO. iCBDCPs do not 'grant credits to others', and so do not meet the definition of 'credit institution'.

The access framework developed in 2017 for non-bank payment service providers to hold settlement accounts in the UK's RTGS system may increase the scope for narrow banks to – in theory – hold reserves. However, it remains the case that access to a settlement account in RTGS is at the sole discretion of the Bank of England.[23]

In defining our models, we make no assumptions about whether a private digital currency is present and widely used, and what technology underlies the CBDC system. For example, we do not assume that DLT is used.

We characterise CBDC itself as electronic, 24x7, national-currency-denominated and interest-bearing access to the central bank's balance sheet. In all models in this paper, CBDC is only issued by the central bank in exchange for eligible securities. In the UK this means that CBDC is denominated in sterling, and for convenience we assume that eligible securities consist only of gilts (alternatively one could specify eligible assets as those currently accepted by the central bank in exchange for reserves as set out under the Sterling Monetary Framework (SMF), with the central bank retaining discretion to choose which of these assets it is willing to accept for any given transaction.[24]) Of course CBDC could also be issued in other ways, for example by spending it into circulation. That however represents flow transactions that cumulate relatively slowly over time, while the focus of this paper is on potentially large stock transactions involving CBDC.

3.2 Assumptions for Balance Sheet Analysis

Our balance sheet analysis is based on a stylised balance sheet representation of a major advanced economy. We draw on data from both the US Financial Accounts and UK Flow of Funds, making the relative size of the assets and liabilities shown in our figures broadly representative of what is reported in the official data.[25] We take as given that a market for reserves with an RTGS system is present, and that it operates separately from the CBDC system. We use the models set out in Section 3.1, but make a number of simplifying assumptions, both for presentational purposes and to improve the tractability of the analysis. Except where explicitly noted, they do not affect the key results. For presentational purposes we also use the

[23] Settlement accounts provide access to reserves for the purposes of settling, in central bank money, obligations that arise from participating in payments systems. This is in contrast to reserve accounts, which are used to participate in the Sterling Monetary Framework. Reserve accounts can also be used for settlement, and reserve account holders may hold a separate settlement account (Bank of England (2018)).

[24] For example, the central bank may choose sell CBDC outright against a relatively narrow pool of eligible collateral, or to lend CBDC under repo against a wider pool of collateral. This is a choice for the central bank to make, taking into consideration its own balance sheet risks. The Bank of England's Sterling Monetary Framework is set out in the 'Red Book' (Bank of England 2015).

[25] For the UK, data from the Office for National Statistics (ONS) 2016 Flow of Funds (Office of National Statistics, 2017) are used. These data are not sufficiently granular to, on their own, provide balance sheet information on all the sectors and assets and liabilities considered in our analysis. Data for the US are from the US Federal Reserve Financial Accounts for 2016.

terminology of the UK financial system. The rest of this section lists our simplifying assumptions.

First, as mentioned, we assume that CBDC is issued by the central bank only in exchange for gilts (i.e. UK central government bonds), as opposed to all other eligible SMF assets. This assumption is only made to streamline the presentation. Second, we assume that, at the time of its initial introduction, CBDC is supplied to the economy by the central bank purchasing gilts outright in exchange for CBDC, rather than via reverse repurchase agreements, that is, by lending CBDC into circulation. This assumption is consistent with the Bank of England's approach to backing banknote issuance (See Bank of England 2016c). Outside of the initial introduction, the central bank stands ready to freely exchange with banks and NBFIs (including those that operate as CBDC Exchanges or iCBDCPs) CBDC for gilts and vice versa, and the central bank acts to match the aggregate quantity of CBDC supplied and demanded in the market in line with its policy objectives. Third, only the central bank, commercial banks, and NBFIs hold gilts directly, while households and firms may only invest in gilts indirectly via a bank or an NBFI. While this is clearly not true in practice – consider, for example, high net worth individuals or the treasury departments of large corporations – it helps to streamline our analysis, by limiting the number of possible scenarios that we need to study. Moreover, in the UK direct holdings of government debt by households and firms are very small compared with total government debt outstanding (this is also true of the United States).[26] Fourth, all commercial banks have reserve accounts at the central bank, while no NBFIs, households or firms have access to reserves; we choose to abstract from non-bank participants in RTGS (such as central counterparties) as they do not play a pivotal role in our analysis. Fifth, we assume that the economy is closed, that is, for simplicity, we abstract from the role of foreign banks and foreign investors. Sixth, two new types of NBFI may exist when households and firms have access to CBDC or to a CBDC-backed financial asset. These are the CBDC Exchange and the iCBDCP, respectively. The role of these agents is described in Sections 5 and 6 and in the appendix. We do not assume that any other type of agent is present.

4 **Financial Institutions Access Model (Model FI)**

4.1 Description of Model FI

The setup of Model FI is illustrated in Figure 3. It shows the interaction between the central bank, the commercial banking sector, the NBFI sector and the household and firm sector. A setup without the presence of CBDC can be visualised by ignoring the red CBDC lines.

Under Model FI, all banks and NBFIs can have a CBDC account at the central bank.[27] While they can individually trade (buy/sell/lend/borrow) CBDC with the central bank in exchange for eligible assets, in aggregate this can only lead to a change in the quantity of CBDC outstanding

[26] In the UK, households directly hold less than 1.5 percent of gilts on issue, and private non-financial companies directly hold less than 0.2 per cent (ONS 2017). In the US, households directly hold less than 9 per cent of the total stock of US Government Treasuries, while non-financial business directly hold less than 1 per cent (Federal Reserve 2017). The very low direct holdings by resident non-financial business may in part reflect decisions by resident multinationals to hold their Treasury security assets in offshore subsidiaries (say, for tax purposes). Such securities are recorded as being owned by non-residents.

[27] Or, to put it in DLT terminology, they can have their own address on the CBDC ledger.

when the central bank pursues a price rule, meaning that it accommodates any demand or supply at the targeted rate. Under a quantity rule the interest rate on CBDC would adjust to equilibrate demand and (fixed) supply. Under either rule, CBDC account holders can trade CBDC among themselves, in exchange for assets (including bank deposits) or goods and services. Banks, in addition to having CBDC accounts, also have reserve accounts at the central bank. To simplify the illustration, we assume no other economic agents have access to reserves. We also assume no change to the purpose of reserves in the financial system. Similarly, we assume that no banks or NBFIs use their access to central bank money to provide an asset to households and firms that is fully backed by central bank money.

Commercial banks maintain debit and credit positions with NBFIs, firms and households (these are represented by the black arrows "Bank Deposits" and "Bank Loans" in Figure 3). NBFIs provide financial services to households and firms, including fund management services, which result in NBFIs having a financial liability to the household and firm sector. Households and firms have no access to CBDC.

The introduction of CBDC provides NBFIs with a new safe liquid asset to hold. It also provides banks and NBFIs with an additional channel for making payments to each other. For example, bank to bank payments can be made through RTGS or through the CBDC system, while NBFI to NBFI payments can be made through the banking system (and settled through RTGS, if required) or directly through the CBDC system. CBDC is therefore a substitute for bank deposits, with substitutability determined by relative functionality and convenience, and actual substitution determined by these in conjunction with relative returns.[28]

4.2 CBDC Introduction Scenario for Model FI

To explore the balance sheet impact of an initial CBDC introduction into the economy, we examine a scenario where the central bank fixes the interest rate on CBDC and allows NBFIs to obtain the quantity of CBDC that they desire at that interest rate. Our illustration assumes that, at this interest rate, NBFIs wish to replace their entire holdings of bank deposits with newly issued CBDC to satisfy their liquidity needs, which for simplicity are assumed to remain constant in sterling terms. This is an extreme case, and while we do not analyse its likelihood, we note that it is a feasible outcome were the interest rate and functionality of CBDC to be sufficiently attractive relative to bank deposits. A more comprehensive analysis, as in Barrdear and Kumhof (2016), would take into account general equilibrium effects whereby the introduction of CBDC may increase economic activity and therefore, in combination with imperfect substitutability between bank deposits and CBDC, the demand for both bank deposits and CBDC.

To understand the potential impact on the size and composition of commercial bank balance sheets, we trace through all the potential movements of assets and liabilities within and across the balance sheets of the central bank, the commercial banking sector, the NBFI sector and the

[28] CBDC also provides NBFIs with a substitute for holding commercial bank certificates of deposit and commercial paper. We do not analyse the scope for substitution away from this type of banking sector liability given that it provides only 3 per cent of commercial banks' sterling denominated funding. We choose instead to focus on the impact on commercial banks' deposit funding.

household and firm sector as NBFIs shift from holding bank deposits to holding CBDC. We focus on the effects on each sector, rather than on individual agents or institutions, because we are interested in sectoral and aggregate effects. Importantly, we assume that the introduction of CBDC is not accompanied by material stress in the financial system. That is, we assume that the transition occurs in an orderly manner.

In each of our scenarios the maintained assumption is that both NBFIs and households and firms have an unchanged demand for liquidity, where liquidity is defined as the sum of bank deposits and CBDC. Therefore, when NBFIs or households and firms attempt to offload deposits that are surplus to their requirements, they do so by exchanging their deposits with banks, against either other assets held by banks, or against alternative non-deposit liabilities offered by banks.

This maintained assumption for liquidity demand means that an increases in CBDC held by NBFIs and households and firms must result in a reduction in deposits of the same magnitude, and this is reflected in the analysis that follows. If this assumption is relaxed, deposits need not always fall when CBDC is introduced. For example, deposits would not fall in circumstances where an NBFI seeks to replace its gilts with CBDC (which could occur via the NBFI exchanging with its bank deposits for CBDC, and its bank using deposits to purchase the NBFI's gilts to acquire the required CBDC).

4.3 Key Insights from Model FI

Figure 4 illustrates different scenarios for Model FI by way of flow charts, while Figure 5 shows the balance sheets corresponding to three of the scenarios in Figure 4. We assume that at the time of the initial introduction of CBDC, NBFIs switch from holding bank deposits ("NBFI Deposits" in Figure 5) to holding CBDC. But whether bank balance sheets shrink depends on the combined behaviour of banks, NBFIs and households and firms.

We begin by recalling that the scenarios can be decomposed into two separate elements: the decision on the part of the NBFI sector to acquire CBDC, and the decision by the same sector to remove bank deposits from its balance sheet. Recall also that we hold constant the quantity of liquidity demanded by firms and households.

The banking sector's balance sheet contracts if banks in aggregate choose to sell their own assets to help accommodate the demand for CBDC. These asset sales can take the form of either sales of gilts to the central bank to directly acquire the CBDC desired by NBFIs, or sales of non-gilt assets to NBFIs in exchange for the deposit withdrawal desired by NBFIs, or sales of non-gilt assets to households and firms in exchange for the excess deposits received by households and firms from NBFIs. A partial list of the scenarios represented in Figure 4 includes: (1) banks sell part of their gilt holdings to the central bank to acquire the CBDC desired by NBFIs, and then sell this newly acquired CBDC to NBFIs in exchange for the unwanted deposits; (2) banks sell part of their gilt holdings to NBFIs in exchange for the unwanted deposits, and NBFIs then on-sell the gilts to the central bank to acquire the desired CBDC; (3) NBFIs acquire CBDC by selling their own holding of gilts to the central bank, and separately banks choose to sell some of

their non-gilt assets (e.g. MBS or ABS) to NBFIs in exchange for the NBFIs' unwanted deposits; and, (4) NBFIs acquire CBDC by selling their own holding of gilts to the central bank, and separately NBFIs remove unwanted deposits from their balance sheet by buying assets from households and firms; households and firms now have excess liquidity and address this by buying non-gilt bank assets in exchange for deposits.[29]

The size of the banking sector's balance sheet will remain unchanged when the source of the gilts sold to the central bank for CBDC is NBFIs, and when either NBFIs, or the households and firms with whom NBFIs have exchanged bank deposits against non-deposit assets, use their deposits to buy non-deposit bank liabilities, thereby changing the liability composition of the banking sector's balance sheet but not its overall size. A partial list of examples whereby NBFIs reduce their deposits includes: (1) NBFIs buy non-deposit bank liabilities in exchange for their deposits, or (2) NBFIs buy assets from households and firms in exchange for deposits, and households and firms then remove this excess liquidity by buying non-deposit liabilities from the banking sector. Note that in these cases, although the size of the banking sector's balance sheet is unchanged, the composition of bank funding is changed.

The choice made by commercial banks between sales of non-gilt bank assets versus sales of non-deposit bank liabilities to NBFIs or households and firms will be influenced by regulatory requirements and by the relative cost of the different options. The choices made by NBFIs, households and firms similarly depend on the relative returns and other characteristics of the available options.

Note that the size of the aggregate banking sector's balance sheet is not per se important for economic outcomes. Instead the critical magnitudes are two balance sheet sub-aggregates that involve the assets and liabilities of banks. On the asset side, the critical magnitude is credit, meaning total funding received by non-bank borrowers, which determines those borrowers' ability to invest and trade. We denote this category by "Total Credit" in Figure 4, which roughly equals the sum of "Loans" and "Other Bank Assets" in Figure 5. On the liability side, the critical magnitude is liquidity, because liquidity affects the ability of non-banks to engage in economic exchange transactions. Liquidity can take the form of bank deposits, cash (ignored here for simplicity because it is small) and, after its introduction, CBDC. Our simplifying assumption is that what matters for aggregate liquidity is the sum of bank deposits and CBDC held by households, firms and NBFIs. In Figure 5 the former is denoted by "Household and Firm Deposits" and "NBFI Deposits", and the latter by "CBDC".

We observe that Total Credit is never directly affected by NBFIs' switch from bank deposits to CBDC. However, there may be second-round effects, through the interest rate on bank loans, that lead to equilibrium changes in the quantity of credit. Some of these effects may be due to regulation. As an example, Basel III requirements place limits on the share of bank funding that

[29] If we relax our simplifying assumption that the only CBDC eligible security is gilts, then there is scope for an interesting further option where banks sell their own-name securities to the central bank in exchange for CBDC (own-name securities are those created by a commercial bank out of loans that it itself has originated). This is a possibility in regimes – such as the Bank of England Sterling Monetary Framework – that accept such securities in their liquidity operations. This option would look much like the situation where banks sell their own holding of gilts to the central bank for CBDC; it would lead to an immediate contraction in the aggregate balance sheet of the banking sector, but not in the first instance reduce the quantity of liquidity (deposits plus CBDC) or credit in the economy.

is ‘unstable’ (through the Net Stable Funding Ratio), and require minimum holdings of liquid assets to cover potential outflows of certain types of funding (through the Liquidity Coverage Ratio). These limits in turn affect banks’ ability to lend. The replacement of NBFI deposits by wholesale funding (Option 2 in Figure 5), or the removal of relatively liquid gilts (Option 1 in Figure 5), could therefore in some circumstances impact regulatory ratios and so affect the quantity or price of credit. Understanding these channels is an important area of future research.

We also observe that Total Liquidity is never directly affected by NBFIs’ switch from bank deposits to CBDC. However, as for Total Credit, there may be second round effects through prices, especially if our simplifying assumption of perfect substitutability between bank deposits and CBDC does not hold, as is likely.

Finally, the willingness of banks to provide CBDC to depositors does not predetermine the impact on their aggregate balance sheet. This can be seen from Figure 4 by observing that all balance sheet outcomes can be obtained whether or not banks provide CBDC for deposits.

5 Economy-Wide Access Model (Model EW)

5.1 Description of Model EW

The setup of Model EW is illustrated in Figure 6. It shows the interaction between the central bank, the commercial banking sector, the NBFI sector, a CBDC Exchange and the household and firm sector. A setup without the presence of a CBDC can be visualised by ignoring the red CBDC lines in Figure 6.

Under Model EW, all banks, NBFIs, CBDC Exchanges and households and firms can have a CBDC account at the central bank. Only banks, NBFIs and CBDC Exchanges can trade CBDC directly with the central bank.[30] Households and firms can instead use a CBDC Exchange to convert deposits to CBDC and vice versa. A CBDC Exchange may be a new standalone entity, or operated by an NBFI or bank. For expositional purpose, in our illustration of Model EW we separate out the operation of CBDC Exchanges rather than consolidate them into the balance sheets of banks or NBFIs. See the appendix for a detailed description of the function and operation of a CBDC Exchange.

To simplify the exposition, we assume that banks and NBFIs do not themselves use the services of CBDC Exchanges given their direct access to the central bank and their ability to transact in the wholesale debt markets to acquire eligible collateral. CBDC account holders can trade CBDC among themselves, in exchange for assets (including bank deposits) or goods and services. Banks, in addition to having CBDC accounts, also have access to reserve accounts at the central bank. To simplify the illustration, we assume no other economic agents have access to reserves. This can be relaxed to allow CBDC Exchanges to have access to reserves, without any change to our key findings. We assume no change in the purpose of reserves, and that no banks or NBFIs use their access to central bank money to provide an asset to households and firms that is fully backed by central bank money.

[30] However, as mentioned in Section 3, this is not a necessary component of this scenario.

Commercial banks maintain debit and credit positions with NBFIs and households and firms (these are represented by the black arrows "Bank Deposits" and "Bank Loans" in Figure 6). NBFIs provide financial services to households and firms, including fund management services, which result in NBFIs having a financial liability to the household and firm sector.

Because households and firms cannot buy CBDC directly from the central bank, they obtain additional CBDC through a CBDC Exchange.[31] In its simplest form, a CBDC Exchange takes bank deposits from households and firms and provides CBDC in return (and vice versa). It may charge a fee or spread for this service. It is also conceivable that banks may choose to absorb any cost to customers, much as the cost of providing cash today is not passed on by banks. To replenish its holdings of CBDC, the CBDC Exchange uses the deposits it receives to purchase gilts, and then uses the gilts to obtain CBDC at the central bank. The CBDC Exchange has an account with at least one commercial bank, in order to be able to accept deposits. For more details on how a CBDC Exchange would operate see the appendix.

5.2 CBDC Introduction Scenario for Model EW

To explore the balance sheet impact of an initial CBDC introduction into the economy, we examine a scenario where the central bank fixes the interest rate on CBDC and allows households and firms to obtain the quantity of CBDC that they desire at that interest rate. Our illustration assumes that, at this interest rate, households and firms wish to replace a significant part of their holdings of bank deposits with newly issued CBDC to satisfy their liquidity needs, which for simplicity are assumed to remain constant in sterling terms. We do not analyse the likelihood of such a shift into CBDC, but note that it is a feasible outcome were the interest rate and functionality of CBDC to be sufficiently attractive relative to bank deposits.

We focus solely on households' and firms' substitution from deposits to CBDC, rather than also considering NBFI substitution from deposits to CBDC, so that we can identify the specific impact that household and firm switching has on bank funding.

5.3 Key Insights from Model EW

Figure 7 illustrates different scenarios for Model EW by way of flow charts, while Figure 8 shows the balance sheets corresponding to the three scenarios in Figure 7. We assume that at the time of the initial introduction of CBDC, households and firms switch from holding bank deposits ("Household and Firm Deposits" in Figure 8) to holding CBDC. But whether bank balance sheets shrink depends on the combined behaviour of banks, NBFIs and households and firms.

The range of potential outcomes for Model EW is very similar to Model FI. The primary difference between the two scenarios is the likely scale of the transition examined when CBDC is introduced. The presence of a CBDC Exchange, and of households and firms that do not

[31] In practice banks may choose to integrate the services of a CBDC Exchange into their consumer offering, in which case individual depositors may not perceive that they are using an exchange, even though – via their bank – they are.

transact directly with the central bank, does not in itself materially alter the outcomes for commercial banks. Given this, many of the insights from examining this model are the same as presented in Section 4. This is of course in itself an important insight.

The banking sector's balance sheet contracts if banks in aggregate choose to sell their own assets to help accommodate the increase in demand for CBDC and the decrease in demand for bank deposits. The banking sector's balance sheet remains unchanged when banks instead sell non-deposit bank liabilities, thereby changing the liability composition of the banking sector's balance sheet but not its size.

But in all cases, as for Model FI, both Total Credit and Total Liquidity are never directly affected by the switch from bank deposits to CBDC, and may in fact, as mentioned previously, increase if the introduction of CBDC liquidity stimulates economic activity and CBDC and bank deposits are not perfect substitutes.

6 Financial Institutions Plus CBDC Backed Narrow Bank Access Model (Model FI+)

6.1 Description of Model FI+

The setup of Model FI+ is illustrated in Figure 9. It shows the interaction between the central bank, the commercial banking sector, the NBFI sector, the CBDC backed narrow bank sector and the household and firm sector. Under Model FI+ access to CBDC is limited to banks and NBFIs. However, at least one financial institution uses CBDC to provide an asset to households and firms that is fully backed by CBDC. We term this asset indirect CBDC, or iCBDC, and note that it may, but does not necessarily, have the same functionality as CBDC. Financial institutions providing iCBDC can be thought of as a type of narrow bank, and we term them iCBDC Providers (iCBDCP). Model FI+ can be thought of a hybrid between Model FI and Model EW.

As in the previous two models, commercial banks maintain debit and credit positions with NBFIs and households and firms (represented by the black arrows "Bank Deposits" and "Bank Loans" in Figure 9). NBFIs provide financial services to households and firms, including fund management services, which result in NBFIs having a financial liability to the household and firm sector. Households and firms buy iCBDC from iCBDCPs using bank deposits, and iCBDCPs allow their customers to cash out their iCBDC for bank deposits. Banks and NBFIs do not themselves use the services of iCBDCPs, given that they have direct access to CBDC. We assume that iCBDCPs have sufficient incentives to set up and continue to operate their service, such as fees for deposits-to-iCBDC conversion, account keeping fees, or a rate paid on iCBDC below the rate paid on CBDC. We also assume that commercial banks are not obliged to provide iCBDC for deposits, because this would amount to guaranteed convertibility of bank deposits into CBDC. As discussed in Section 2.4, this would be a highly undesirable feature.

6.2 CBDC Introduction Scenario for Model FI+

To explore the balance sheet impact of an initial CBDC/iCBDC introduction into the economy, we examine a scenario where the central bank fixes the interest rate on CBDC, where the interest rate on iCBDC equals that on CBDC because iCBDCPs recover their costs through fees rather than spreads, and where households and firms are free to obtain, through iCBDCPs, the quantity of iCBDC they desire at the CBDC/iCBDC interest rate. Our illustration assumes that, at this interest rate, households and firms wish to replace a substantial part of their holdings of bank deposits with newly issued iCBDC to satisfy their liquidity needs, which for simplicity are assumed to remain constant in sterling terms. We do not analyse the likelihood of such a shift, but note that it is a feasible outcome were the interest rate and functionality of iCBDC to be sufficiently attractive relative to bank deposits. We focus solely on households' and firms' substitution away from deposits to iCBDC (and the associated acquisition of CBDC by iCBDCPs), rather than also considering NBFI substitution from deposits to CBDC.

6.3 Key Insights from Model FI+

Figure 10 illustrates different scenarios for Model FI+ by way of flow charts, while Figure 11 shows the balance sheets corresponding to three of the scenarios in Figure 10. We assume that at the time of the initial introduction of CBDC, households and firms switch from holding bank deposits ("Household and Firm Deposits" in Figure 11) to holding iCBDC. But whether bank balance sheets shrink depends on the combined behaviour of banks, NBFIs and households and firms. The range of potential outcomes for Model FI+ is very similar to Model EW. Given this, many of the insights from examining this model are the same as presented in Section 5. One exception is that, compared to Model EW, the central bank may have more limited control over the relative attractiveness of iCBDC and bank deposits, because of the possibility that iCBDCPs offer a time-varying interest rate spread of iCBDC relative to CBDC.

7 **Digital Bank Runs?**

7.1 Preliminaries

In Sections 4-6 we have studied the balance sheet dynamics associated with an orderly introduction of CBDC into an economy where CBDC is not yet present, and where bank deposits are the only significant medium of exchange. We now turn to studying an environment where CBDC is already established as a medium of exchange alongside bank deposits, and where the economy experiences a sudden loss of confidence in the banking sector that results in a large-scale attempt on the part of non-banks to switch from holding bank deposits to holding CBDC (or iCBDC). The balance sheet issues, namely the attempts to acquire large additional stocks of CBDC, are therefore very similar to those discussed above. The differences are in the potentially very large size of the desired switch into CBDC, and in the assumption that this switch is not orderly, but is instead taking place in an environment of financial market panic. During discussions of the pros and cons of CBDC, concerns about the vulnerability of the banking system to such 'digital bank runs' are very common.

Our main point in this section will be that, as long as the core design principles for a CBDC system of Section 2 are respected, such concerns are to a significant extent misguided, in that they either presume CBDC transmission channels that appear to exist in partial equilibrium, but that do not survive a general equilibrium analysis, or that they consider scenarios that are as possible in today's financial system as they are in a world with CBDC.

One example of the latter is runs from bank deposits to cash. Such runs can of course happen.[32] But this is true equally in a world with and without CBDC. The key question here concerns not cash but CBDC, and it is whether the presence of CBDC opens up *new* possibilities of system-wide runs by non-banks on the banking system that are not present in a world without CBDC.

As set out in Section 2, the core design principles for a CBDC system are that CBDC must be (i) interest-paying, with an adjustable rate, (ii) distinct from, and not convertible to, reserves, (iii) no explicit or implicit central bank guarantee of convertibility against deposits, and (iv) issued only against eligible securities. The effect that these principles have on a run scenario are explored below in the context of both a CBDC quantity and a CBDC price rule.

We begin with the first core principle, the adjustable interest rate on CBDC. Here we need to distinguish between CBDC quantity rules and CBDC price rules. Under a CBDC quantity rule, the adjustment mechanism for the interest rate on CBDC should be designed in a way that continuously clears the market. For example, if the central bank targets a CBDC-to-GDP ratio of, say, 15%, and at some point in time, and at prevailing CBDC interest rates, the market demands more CBDC than this target, the interest rate on CBDC must drop until the market clears at the desired quantity. An efficient mechanism needs to exist to facilitate this adjustment. Further research into the potential design of this mechanism would be a valuable extension to the CBDC literature. For example, this research could usefully establish whether it is necessary for the mechanism to make adjustments in near real time, or whether small delays in adjustment can be tolerated if the market believes the central bank will consistently and credibly act to match the quantity of CBDC demanded to the quantity target.[33] This assessment would need to consider the speed and volume of flows that could be possible with CBDC, both during normal times and in situations of financial market stress.

Under a CBDC price rule, the main response to changes in the demand-supply balance for CBDC will of course come through quantity adjustments, which we will discuss below. But even here, the central bank can use discretion in order to quickly respond to financial market dislocation and an attempted run into CBDC, by lowering the CBDC interest rate, if necessary drastically, although beyond some point this could face political economy barriers. Unlike for the interest rate on reserves, which would continue to be adjusted in the current fashion, at discrete and fairly long intervals measured in weeks or months, adjustments to the interest rate on CBDC could and should be made quickly and frequently if circumstances demand it.

[32] The exception is when convertibility into cash is suspended or curtailed in an emergency, as for example happened in Greece and Cyprus during the recent crisis.

[33] Agents may not deviate from a parity exchange rate today even in the face of supply/demand imbalance if they know that tomorrow the central bank will adjust policy to ensure balance at parity, as deviating would result in a capital loss tomorrow.

We now turn to the remaining core principles set out in Section 2, which concern the restrictions on what assets the central bank will accept in exchange for CBDC. The principles are that CBDC is issued against eligible assets of the central bank's choosing−most likely the assets against which reserves are currently issued−but not against bank deposits, reserves or cash. In many major economies, including the UK, the set of central bank eligible assets is considerably broader than domestic government securities, with the risks associated with non-government assets managed through haircuts (that is, to manage its risk exposure, the central bank may lend against riskier assets but only at a discount to their market value). Conversion into CBDC of such a large pool of available assets can in principle quickly accommodate a run into CBDC, by making it easier for banks to obtain the desired CBDC. It does not however make it easy to eliminate exposures to bank deposits in a bank confidence crisis, for example in an environment where some households and firms do not wish to hold bank deposits at any price, irrespective of their return differential with CBDC. This is a subject to which we will return below.

The most problematic design feature of a CBDC system, as discussed in Section 2.3, would be for banks, and therefore by implication the central bank, to have to guarantee unlimited convertibility of bank deposits into CBDC. A guarantee of unlimited convertibility by commercial banks would – to make it fully credible even in cases where banks are no longer able to obtain CBDC or eligible assets in private markets – require the central bank to also guarantee convertibility. In that case, if households and firms wanted to quickly shift out of bank deposits at scale, they could do so, because once banks are no longer able to obtain CBDC, and once they have run out of eligible assets to obtain CBDC from the central bank, the central bank would be obliged to provide additional CBDC against bank-issued IOUs. This however would open the door to aggregate bank runs, with a counterpart in the central bank becoming a large, and potentially partly unsecured, creditor of the banking system. The central bank may under certain circumstances wish to become such a large creditor, but this should not be at the initiative of households and firms, it should be a policy decision.

We have already discussed, in Section 2.3, how the absence of a guarantee of convertibility of bank deposits into CBDC does not imply that bank deposits do not trade at parity with other forms of central bank money. The reason is that parity can be accomplished in other ways. Specifically, under a CBDC quantity rule, CBDC trades at par because the interest rate on CBDC, rather than the exchange rate between CBDC and other forms of central bank money, clears the market. And under a CBDC price rule the central bank issues cash, reserves or CBDC against eligible assets at parity between these different forms of central bank money, while commercial banks' settle interbank deposit flows in reserves at parity. Commercial banks also exchange deposits for cash at parity, which supports parity between different forms of central bank money and deposits, but is not strictly required. It is, however, important that there are sufficient CBDC eligible assets available to enable private participants to take advantage of the arbitrage opportunity that arises from temporary deviations from CBDC-bank deposit parity.

Convertibility of bank deposits into CBDC does therefore not have to be ensured by banks themselves, and the central bank therefore does not need to stand ready to accept bank IOUs as an eligible asset when issuing CBDC. Instead, all that is needed is that there is a market where

bank deposits can freely be traded against CBDC and CBDC eligible securities, and that this market clears through a mechanism other than adjustments in an exchange rate between bank deposits and CBDC. Whether commercial banks participate in such a market is a business decision, not a design feature of the monetary system.

7.2 Digital Bank Run Scenarios in General Equilibrium

We now attempt to construct scenarios of large-scale digital bank runs, and we explain where such scenarios can run into contradictions in general equilibrium. Assume that a large group A of private agents panics and sells bank deposits at scale in order to obtain CBDC. For the sake of our argument, we assume that this group consists of half of all households, firms, and NBFIs. It is assumed that group A does not hold eligible assets, and that banks do not hold CBDC on their balance sheets. It is also assumed that the central bank fixes the interest rate on CBDC, not its quantity.[34] What happens next depends on whether, where and how the additional CBDC demanded by group A is available. There are three sets of scenarios.

The first set of scenarios is that there is a group B of private non-bank agents that consists of the other half of all households, firms, and NBFIs, and that these agents are willing to sell CBDC to group A. In this case CBDC, but also bank deposits, simply change hands between different agents, while there is no change in their aggregate quantity. What looks, from the vantage point of group A, like a successful digital bank run, is in general equilibrium no run on the aggregate banking system at all. There are several variants to this scenario, and again there is no aggregate bank run in any of them. The first variant is one where commercial banks serve as intermediaries for group A, by entering the private market to buy CBDC from group B, and then selling it to group A. Because banks buy the additional CBDC by issuing new deposits to group B, and group A subsequently withdraws its deposits to obtain the CBDC, this does not change the quantity of aggregate deposits at all, it only changes their distribution. The second variant is one where group B is willing to sell eligible assets rather than CBDC to group A. As before, group B ends up with the bank deposits of group A, and the latter ends up with the desired CBDC, obtained by exchanging their newly acquired eligible assets against CBDC at the central bank. The third variant is one where commercial banks serve as intermediaries for group A, by entering the private market to buy eligible assets from group B, and then converting the eligible assets into CBDC before selling it to group A. Because banks buy the additional eligible assets by issuing new bank deposits to group B, and group A then withdraws its deposits to get the CBDC, the aggregate quantity of deposits has not changed at all, only its distribution.

It could now be argued that a run on a single bank can be sufficient to trigger systemic financial sector problems, and that the presence of CBDC makes such a run more likely because of its electronic, click-of-a-button nature. But this is not convincing. The reason is that bank deposits at different financial institutions are also electronic and easy to use, and a run that moves existing deposits from a single troubled institution to other institutions is in this regard not

[34] Note that a scenario where the central bank fixes the quantity of CBDC and allows the interest rate to adjust in close to real time is very similar to one where it fixes the interest rate but uses discretion to adjust the interest rate quickly in response to an attempted run. The difference is that in the former case the interest rate adjustment is automatic, while in the latter case it requires a policy decision.

fundamentally different from a run via CBDC. But such a run is of course perfectly possible today, in a world without CBDC. This can therefore not be an argument against CBDC.

A more convincing argument is that a run on a single bank is more likely because the presence of CBDC reduces to zero the search cost of finding a low risk (or indeed risk-free) provider of liquid assets that can, unlike cash, be held at large volume at low cost. Depositors will inherently know that CBDC is 'safe', whereas determining which commercial banks are safe can be costly in a period of financial stress where banks' liquidity position (and indeed solvency) can shift rapidly. But there are arguments in the other direction: the presence of CBDC could potentially make it easier and faster to resolve an individual troubled institution, by giving the authorities the option of repaying its depositors in safe CBDC at an early stage, and then resolving the institution without the danger of contagion effects to other parts of the financial system which would otherwise likely occur when the deposits of the troubled institution can temporarily not be used and are perceived to be at risk of at least partial default. Because a CBDC-based resolution can be carried out almost instantly, it reduces the potential for contagion. Because bank depositors know this ex-ante, this may in fact reduce the probability of a bank run compared to a world without CBDC. We note that this resolution mechanism amounts to the central bank accepting bank IOUs in exchange for CBDC in an emergency. However, this would be at the central bank's discretion rather than automatic, and the central bank would only accept the IOUs of a specific troubled institution rather than of all banks (and then potentially only up to some deposit insurance limit). Engert and Fung (2017) also conjecture that, to the extent that the presence of widely accessible CBDC increases the credibility of the run threat, banks may respond ex ante by reducing their risk taking or holding higher capital buffer stocks.

The second set of scenarios is that there is no non-bank group B (households, firms or NBFIs) that is willing to supply CBDC or eligible assets to group A, or to banks as intermediaries for group A, but that commercial banks have excess supplies of eligible assets on their balance sheets. When group A demands additional CBDC, banks may choose to liquidate their eligible assets at the central bank against CBDC, and sell this CBDC to group A. The bank balance sheet shrinks by the amount of bank deposits withdrawn against CBDC. Similar to the balance sheet scenarios in Sections 4-6, this is an orderly reduction in the size of bank balance sheets that, at least initially, changes neither the total amount of credit to non-bank borrowers nor the total amount of liquidity in the economy. Because the eligible assets liquidated by banks are excess supplies, this by assumption also has no critical effects on regulatory ratios. As long as the available excess supplies of eligible assets do not exceed the demand for CBDC of group A, this need not cause any serious problems for the banking sector or its customers.

At this stage it is worth considering if there are enough eligible assets to accommodate a large-scale increase in CBDC. As at the end of 2016, the total value of UK sight deposits held by the private sector (excluding banks and non-residents) was approximately £1300 billion, with a further £650 billion held in term deposits, while the total market value of gilts held by the private sector was around £1430 billion.[35] A significant portion of gilts may not be freely tradable, however, due portfolio restrictions on insurance companies and pension funds (which

[35] Deposit data from Bank of England Statistical 'Bankstats (Monetary & Financial Statistics) tables' Table B1.4. Gilts data are from the UK Debt Management Office, 'DMO Distribution of Gilt Holdings.' Both accessed on 1 December 2017.

hold around two-fifths of total gilts), price insensitivity for gilts held offshore (around one quarter of total gilts),[36] and regulatory requirements on financial institutions (around 10 per cent of total gilts). If CBDC eligible assets are those accepted under the SMF, however, including own-name securities, then they would amount to more than the stock of deposits.

This takes us to the third set of scenarios, which is that the run to CBDC is so large that, at the current CBDC interest rate, neither banks nor group B are willing to part with sufficient quantities of CBDC or eligible assets to satisfy the demand of group A. What happens in this third set of scenarios is again a function of the policy rule for CBDC issuance.
Assume first a CBDC quantity rule. Under this regime any nascent increase in the demand for CBDC can be eliminated by a drop in the interest rate on CBDC. But there are potential limits if this requires a highly negative interest rate, and if further reductions of the interest rate below this level become politically difficult.

At this point, the central bank might be forced to switch to a price rule. Assume therefore a CBDC price rule where the central bank fixes the interest rate on CBDC at the lowest politically acceptable level, and assume that even at this penalty rate group A wants to convert deposits to CBDC at (almost) any price, perhaps because it is concerned about the solvency of banks.

In the first instance, under the assumption that no more CBDC eligible securities can be purchased, deposit-CBDC parity might break. This is because the elimination of deviations from parity relies on arbitragers being able to purchase a security for deposits and sell the same security for the same nominal value in CBDC to the central bank; if there are no more securities available to purchase (or alternatively if the price of CBDC eligible securities rises to such an extent that the central bank chooses to stop purchasing them in order to protect its balance sheet), this arbitrage mechanism breaks down.

However, parity does not have to break, because another price, the interest rate on bank deposits, can adjust. Given the large reduction in demand for bank deposits at given interest rates, the interest rate on bank deposits is likely to increase relative to the policy rate and the CBDC rate, to incentivise households and firms to hold deposits. Because the interest rate on bank deposits constitutes the marginal cost of funding for banks, competitive banks would pass this increase on to borrowers in the form of higher lending rates.

Until this point, deposits have been destroyed only to the extent that banks have chosen to sell their own holdings of CBDC, or of CBDC eligible securities. As discussed in Sections 4-6, this destruction of deposits does not entail an immediate reduction in either economy-wide credit provision or economy-wide liquidity provision. However, the increase in deposits rates would trigger second round effects, by reducing the demand for loans. This in turn would lead to repayments of loans, and loan repayments are made through the destruction of existing bank deposits. In this case there would then be a reduction in credit and liquidity provision. But

[36] While these could be repatriated to the UK – particularly as gilt prices rise in a crisis – we conjecture that these overseas holdings may be stickier then those held onshore in part because they are less likely to be held for liquidity purposes and more likely to be held in investment funds (including sovereign wealth funds) that may have portfolio requirements that prevent a material reduction in their gilt holdings irrespective of price moves, at least over short time horizons.

crucially, such loan repayments cannot become extremely large overnight or inside a few days, while bank runs are clearly almost instantaneous phenomena. Relatedly, loan repayments are, to a significant extent, asset-side events for banks, and require explicit decisions that take time, while bank runs are liability-side events, where banks are mostly passive responders. These are very different phenomena. More importantly, none of the price channel adjustments outlined above have any necessary connection with CBDC, and are therefore as feasible in a world without CBDC as in a world with CBDC, just as in a run from bank deposits to cash.

As a final point, we note that the third scenario discussed above is very extreme indeed, entailing a loss of confidence in the entire banking system. In such a scenario, historical precedent suggests that, irrespective of the existence of a CBDC or not, the central bank and government may take measures to minimise disorder earlier in the panic, such as curtailing deposits-to-cash and deposits-to-CBDC convertibility, imposing capital controls and/or nationalising banks. The central bank would also be free, at its discretion rather than as an automatic response, to temporarily accept bank deposits, in this case from all banks, in exchange for CBDC. Because this amounts to the central bank accepting unsecured IOUs from banks, at an interest rate of its choosing, this would limit the increase in funding cost for the banking system.

We summarize the foregoing as follows: First, runs on individual financial institutions, or system-wide runs from bank deposits into cash, are as feasible in a world without CBDC as in a world with CBDC, and given the advantages of CBDC in case it comes to a bank resolution, may be less likely with CBDC. Second, system-wide runs that attempt to reduce the absolute quantity of bank deposits can only succeed through asset-side adjustments of banks, and again their feasibility does not depend on the presence of CBDC while their likelihood may be lower with CBDC. Third, attempts to drastically increase the quantity of CBDC relative to bank deposits can be accommodated through the appropriate design of the CBDC system, and this accommodation only encounters limits under very extreme circumstances, including a limit to how negative the interest rate on CBDC can become, and a limit on the availability of eligible assets that the central bank is willing accept in exchange for CBDC. It is of course prudent to worry about all these possibilities, but they make for a far weaker argument against CBDC than what popular partial equilibrium arguments about digital bank runs could lead one to believe.

8 Conclusions

Central bank digital currencies (CBDC) raise many fundamental questions about the architecture and operation of the monetary and financial system, and of the economy more broadly. To make discussions about the potential impact of CBDC practically useful, it is essential to start with a clear description of how a CBDC system might operate in the real world. An essential aspect of this is the balance sheet dimension of CBDC. In this paper we therefore start by describing the balance sheet implications of an initial introduction of CBDC into three hypothetical but plausible model economies that differ in the sectors that are able to access CBDC. We then discuss the subject of digital bank runs in a world with CBDC.

For the end-users of CBDC, the digital currency is a substitute for commercial bank deposits. Its balance sheet implications are therefore closely connected to the balance sheet implications for commercial banks and for NBFIs. It is therefore critical to understand the impact of CBDC not only on the size of bank balance sheets, but also on economically important dimensions of those balance sheets, most importantly on bank funding, total private credit and total provision of a liquid medium of exchange.

We show that, if CBDC is introduced in an orderly manner, the size of bank balance sheets may be, but need not be, reduced. Indeed, CBDC does not necessarily lead to a contraction in bank funding. But more importantly, there are, up to a first approximation that abstracts from second round and price-mediated effects, no adverse effects on private credit or on total liquidity provision to the economy. Modelling second round effect – and particularly price effect – is an important area for future research.
On the subject of digital bank runs, we set out core principles for a CBDC monetary system that ameliorate the risk of such events. These principles also support an orderly introduction of CBDC. These are that CBDC must be (i) interest-paying, with an adjustable rate, (ii) distinct from, and not convertible to, reserves, (iii) no explicit or implicit central bank guarantee of convertibility with deposits, and (iv) issued only against eligible securities. Under fractional reserve banking, bank runs can never be completely ruled out - the best that can be accomplished is to minimize the probability of their occurrence. We argue that a CBDC system would contribute to doing so, based on the above core principles together with the ability to resolve institutions much more efficiently through the use of CBDC. But residual risks remain. Under a CBDC quantity rule, the risk is that the required interest rate on CBDC might drop so far below zero that this would no longer be politically acceptable, even as a temporary phenomenon. And under a CBDC price rule, the risk is that the market could run out of eligible assets to convert into CBDC, even with the current high levels of government debt and other potentially eligible debt securities in many developed economies. Implementing the core principles is also non-trivial. In particular, an effective mechanism would need to be designed to allow the rate on, or quantity of, CBDC to effectively adjust in response to shifts in demand for this form of central bank money.

As noted at the outset, this paper is intended to serve as useful background material for research in the field of CBDC. The Bank of England has published a detailed set of research questions on CBDC, covering economic, financial stability and technological aspects of CBDC.[37] From the insights derived in this paper, we think that useful further research could first of all examine departures from our implied assumption of perfect substitutability of bank deposits and CBDC for liquidity purposes. Specifically, what is the substitutability between bank deposits and CBDC, or in other words what are the interest-semi elasticities of demand for these two types of liquidity? Depending on the answer to this question, one could then examine the following questions: How might commercial banks competitively respond to the introduction of CBDC? How will they choose to adjust the composition and quantity of their funding, given the cost of different funding options and regulatory requirements? What effect would this have on overall bank funding costs, credit provision, and on liquidity provision? What novel tools for monetary

[37] A detailed set of CBDC research questions has been set out by the Bank of England. It is available at http://www.bankofengland.co.uk/research/Documents/onebank/cbdc.pdf.

policy and/or financial stability could exist with a CBDC and how could they be used? How could CBDC affect the central bank's balance sheet risk? How can incentives in the system be designed to ensure participation and stability? And, as discussed above, what mechanisms can be used to facilitate an efficient adjustment of the rate on, or quantity of, CBDC in response to shifts in demand for this form of central bank money?

Appendix: CBDC Exchanges

In its simplest form a CBDC Exchange performs the following three types of trades:

1. It sells/buys CBDC to/from households and firms in exchange for bank deposits.
2. It sells/buys bank deposits to/from other private sector counterparties in exchange for central bank eligible collateral (for simplicity we assume gilts).
3. It sells/buys gilts to/from the central bank in exchange for CBDC.

The CBDC Exchange may charge a fee or spread for this service. It has an account with at least one commercial bank in order to hold commercial bank deposits. The role of the CBDC Exchange and its interaction with other agents in the economy is illustrated in Figure 12.

Setup and Operation

The setup and operation of a CBDC Exchange can be broken into 5 stages.

Stage 1. Capital is raised to operate a CBDC Exchange. Starting capital is required to fund a float so that the Exchange has a sufficient stock of CBDC and bank deposits to immediately meet household and firm demand. The size and composition of the float depends on: the anticipated size and direction of the CBDC-to-deposits transactions requested by households and firms; the frequency at which the CBDC Exchange intends to rebalance its float to its target level (the more frequent the rebalancing and/or the more balanced the direction of requested flows the smaller the required float); and the depth and liquidity of the markets within which the CBDC Exchange operates (the more liquid the market, the easier it is to satisfy demand without having to rely on carrying sizeable balance sheet exposures).

Stage 2. The capital is initially subscribed in the form of bank deposits. However, the float will initially need to be entirely in CBDC given the one-sided nature of net flows in the introductory phase of a CBDC, while in steady state the float will be comprised of both CBDC and bank deposits. The CBDC Exchange coverts its float capital of bank deposits to CBDC by buying gilts in the market, and then selling these gilts to the central bank for CBDC.

Stage 3. The CBDC Exchange sells CBDC (or bank deposits) to households and firms for bank deposits (or CBDC). The CBDC Exchange may charge a fee or spread to households and firms.

Stage 4. Once the composition of the float has deviated sufficiently from its desired composition, the CBDC Exchange rebalances the float. It does so by buying/selling CBDC for gilts with the central bank, and buying/selling gilts or CBDC for bank deposits with banks and NBFIs.[38]

Stage 5. Repeat stages 3 and 4

[38] Rather than buy/sell gilts to the central bank, the CBDC Exchange could also engage in repos with the central bank to lend/borrow gilts against borrowing/lending CBDC. The various balance sheet effects that we consider would be the same.

Fees and Spreads

To incentivise a CBDC Exchange to set up and provide an ongoing service, it will require some form of compensation. This may, for example, be in in the form of an ad valorem or fixed fee, or a spread charged to households and firms for each transaction. Alternatively, banks may choose to subsidise CBDC Exchange costs as a service to their customers in a similar way to how they currently subsidise cash distribution costs.

Balance Sheet Impact of Setting Up the CBDC Exchange

When a CBDC Exchange is set up, the impact on commercial banks' balance sheets will be limited to the size of the CBDC Exchange portion of the float. The float of the CBDC Exchange is likely to be small compared with the magnitude of the exchange flows it facilitates, and therefore the impact of the float on the balance sheet of the commercial banking sector can be expected to be small. Nonetheless, we set out these effects below for completeness.

Stage 1 – Starting Capital. If the source of the CBDC Exchange starting capital is through subscriptions paid, in the form of bank deposits, by NBFIs or households and firms, there is no effect on banks' balance sheet beyond a shift in the ownership of bank deposits from NBFIs and households and firms to the CBDC Exchange. If the source of starting capital is subscriptions from the banking sector, banks' balance sheet expands, as deposits are created on the liability side and an equity asset is created on the asset side.

Stage 2 - Float. The CBDC Exchange can acquire CBDC for its float in two different ways. First, if it purchases gilts from NBFIs, then there will be no immediate effect on bank balance sheets beyond a change of deposit holder, from the CBDC Exchange to NBFIs. Second, if it purchases gilts from banks, then banking sector deposits are destroyed and the banking sector's balance sheet contracts.

Balance Sheet Impact of Operating the CBDC Exchange

Because the CBDC Exchange periodically rebalances it float back to its target allocation, there is likely to be no material ongoing impact on banks' balance sheets from the operation of the CBDC Exchange, as it merely facilitates the exchange of assets rather than building up positions itself. However, shifts in the target composition of the float will have an effect on the banking sector balance sheet as it affects the amount of deposits that the CBDC Exchange holds. But even this effect is likely to be negligible given the small size of the float. It is set out below.

Stage 3. When the CBDC Exchange swaps CBDC against bank deposits, there is no effect on bank balance sheets beyond the CBDC Exchange becoming the holder of deposits rather than a household or firm.

Stage 4. When the CBDC Exchange rebalances its float back to target, the effects are the same as for Stage 2 described above.

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Figure 1. The Interest Rate and Convenience Yield on CBDC

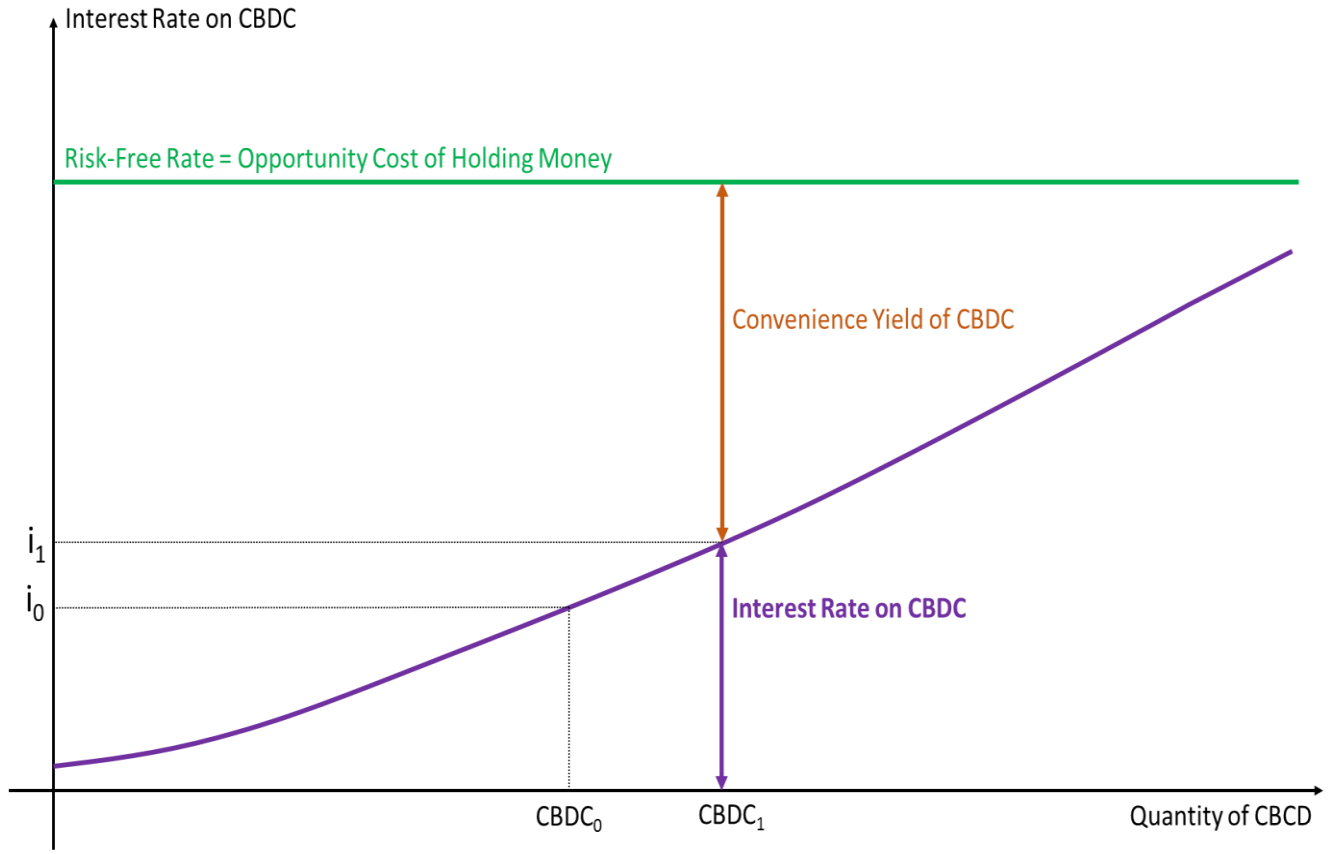

Figure 2. CBDC Models by Access

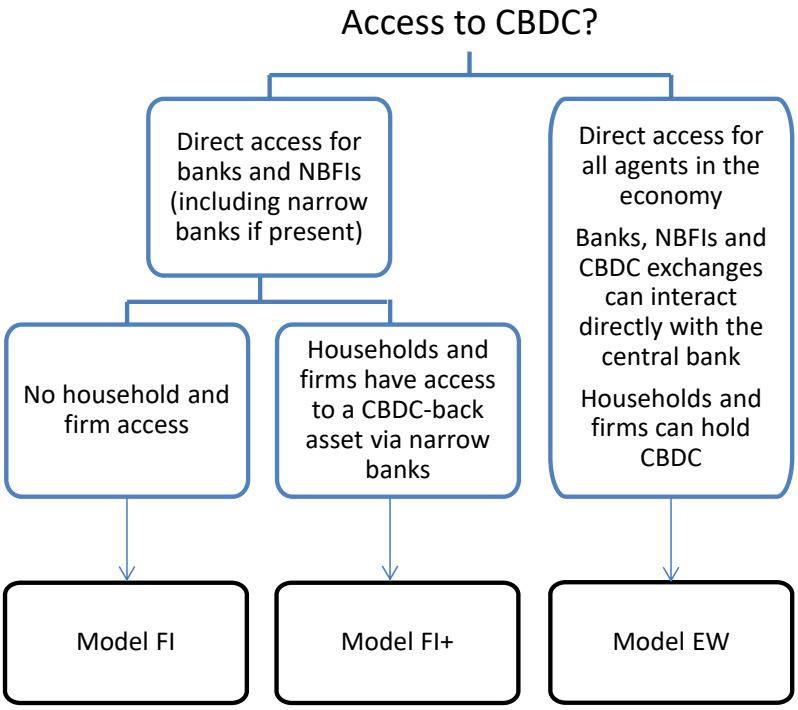

Figure 3. Model FI – Map

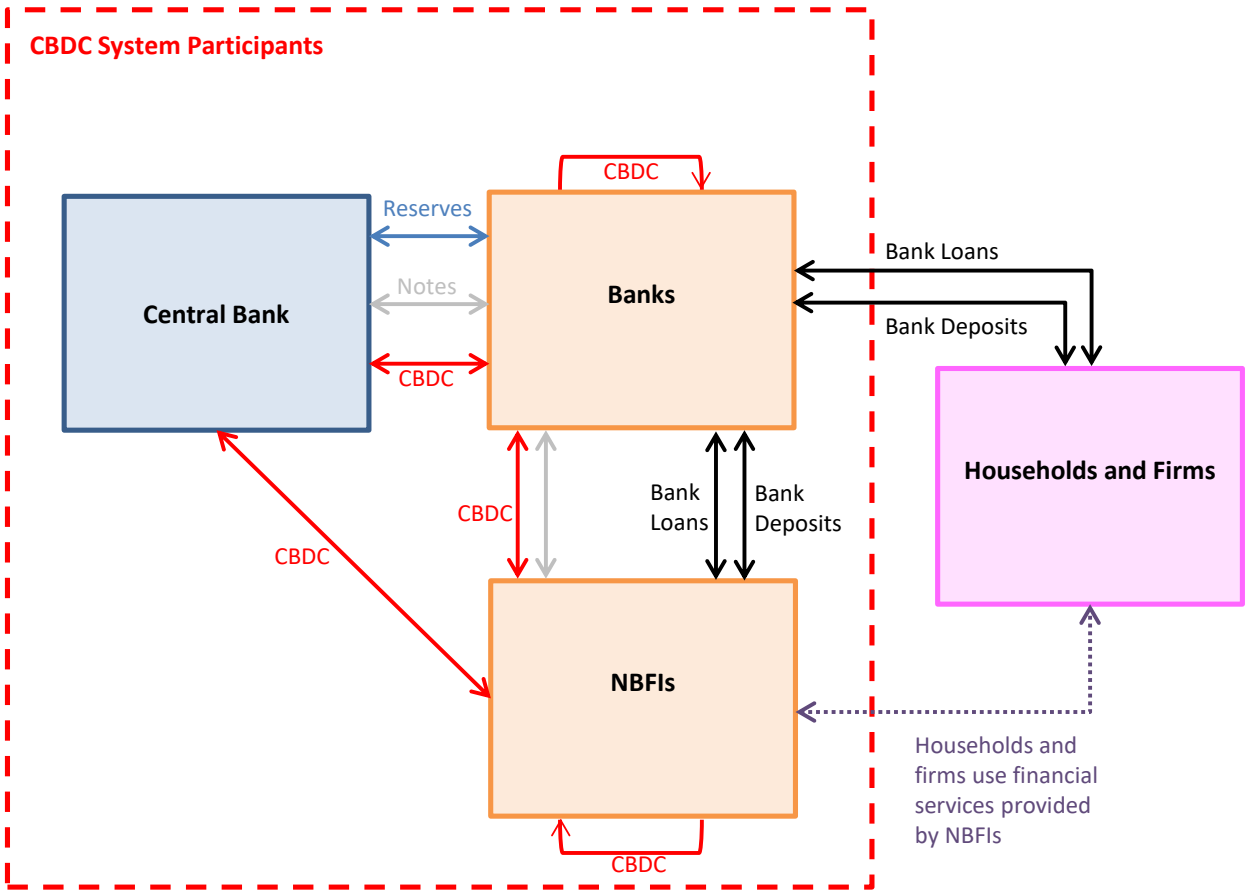

Figure 4. Model FI – NBFIs Switch from Deposits to CBDC

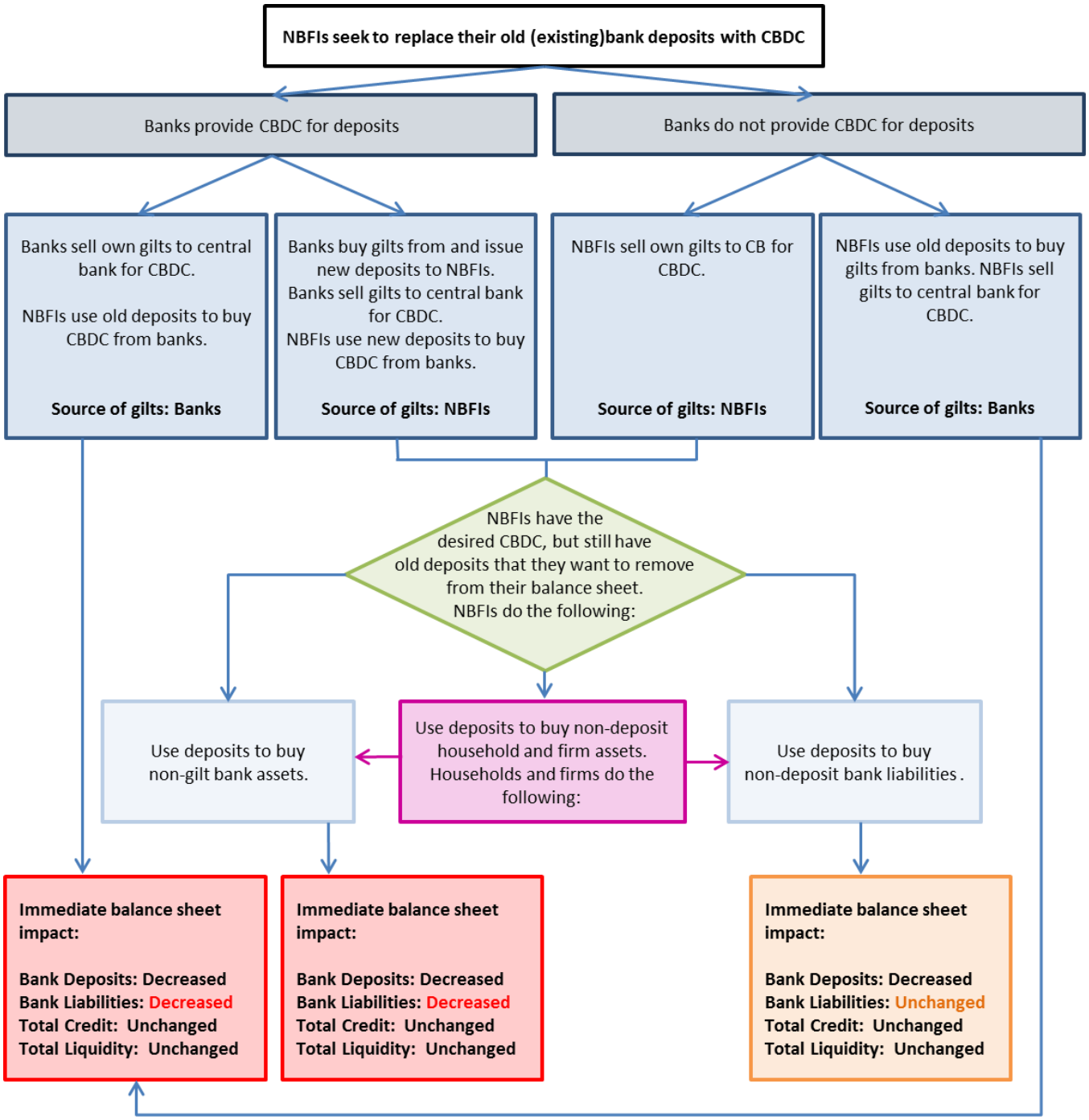

Figure 5. Model FI – Impact of NBFIs Replacing Deposits with CBDC

Figure 6. Model EW – Map

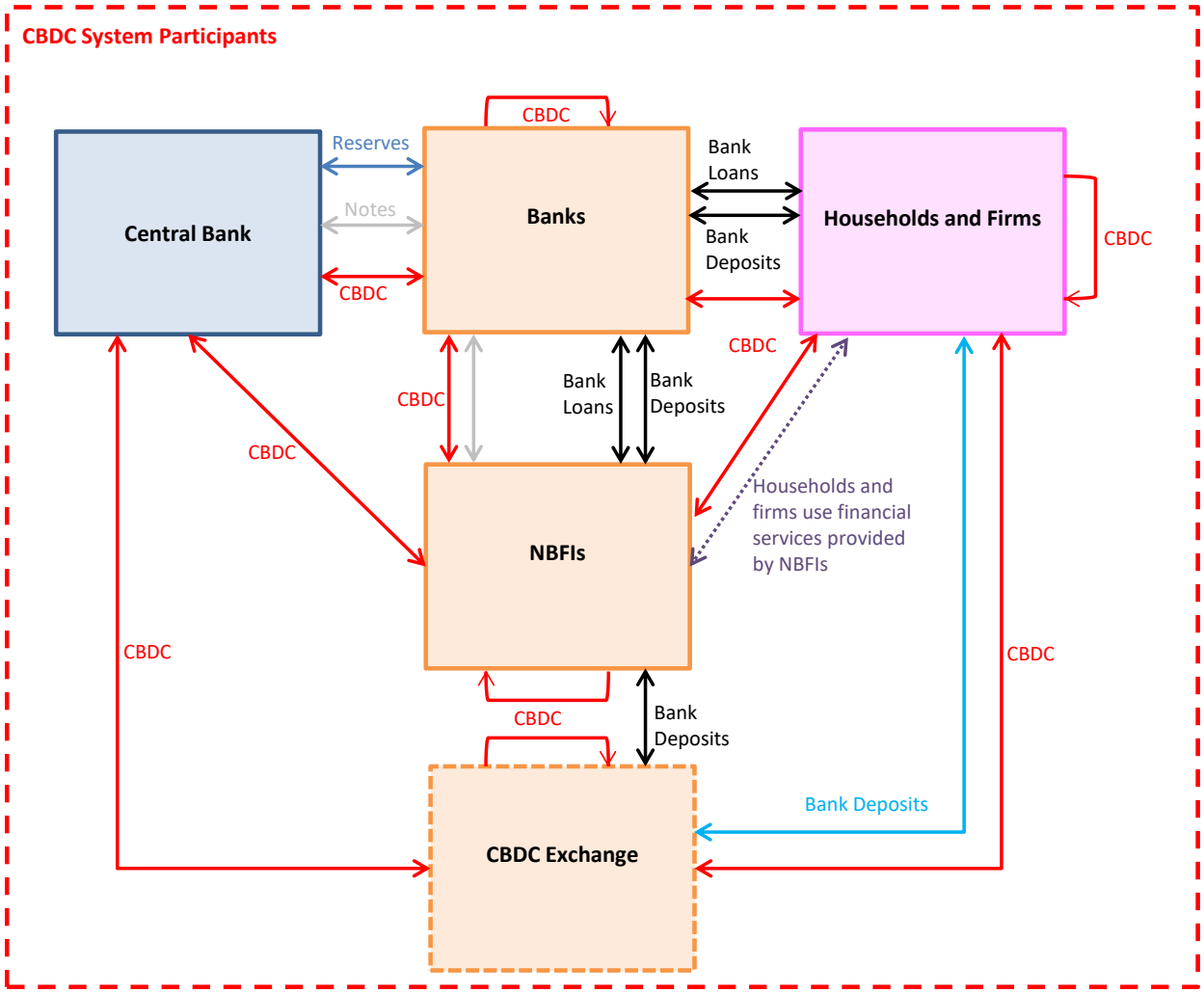

Figure 7. Model EW – Households and Firms Switch from Deposits to CBDC

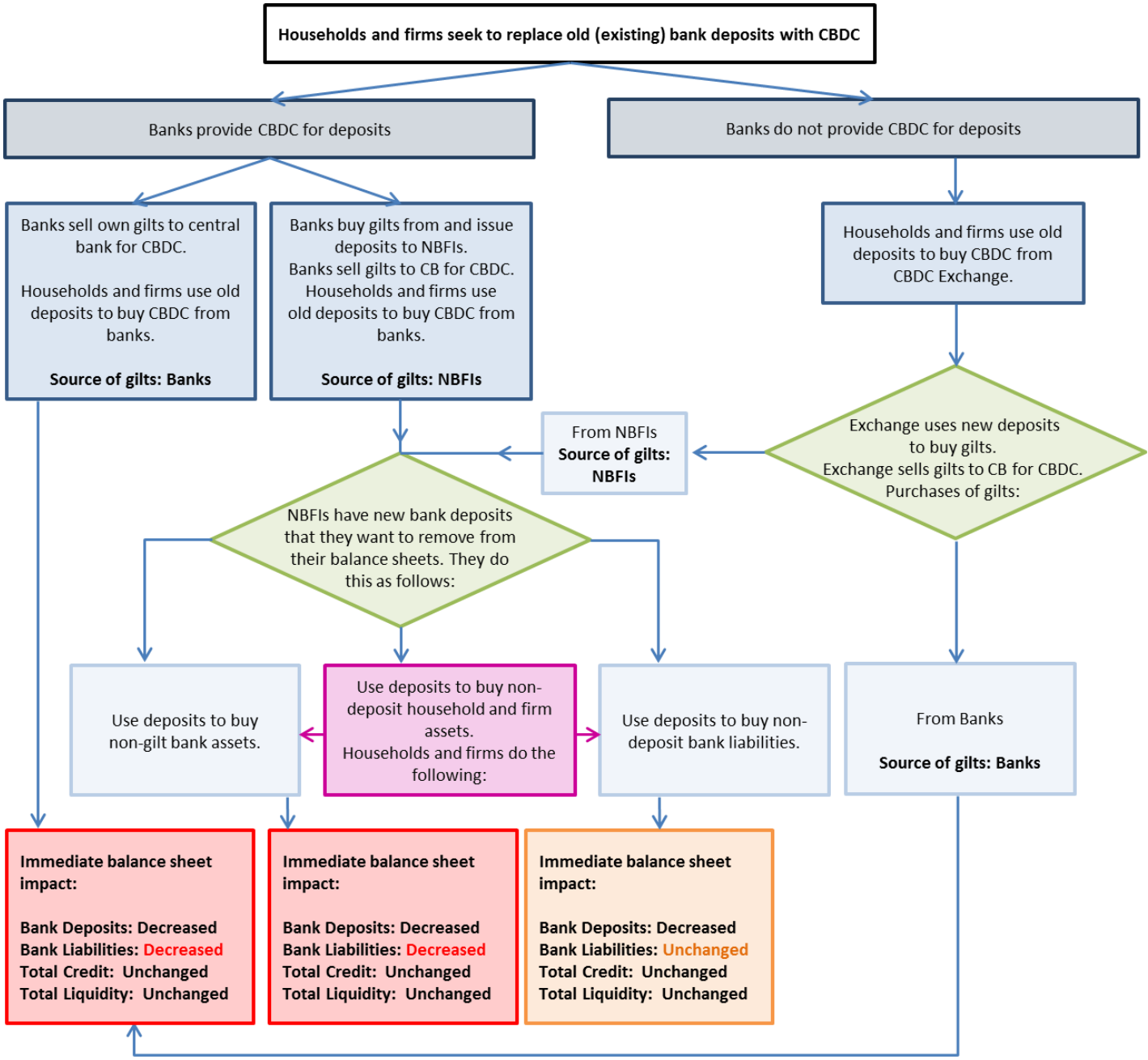

Figure 8. Model EW – Impact of Households and Firms Replacing Deposits with CBDC

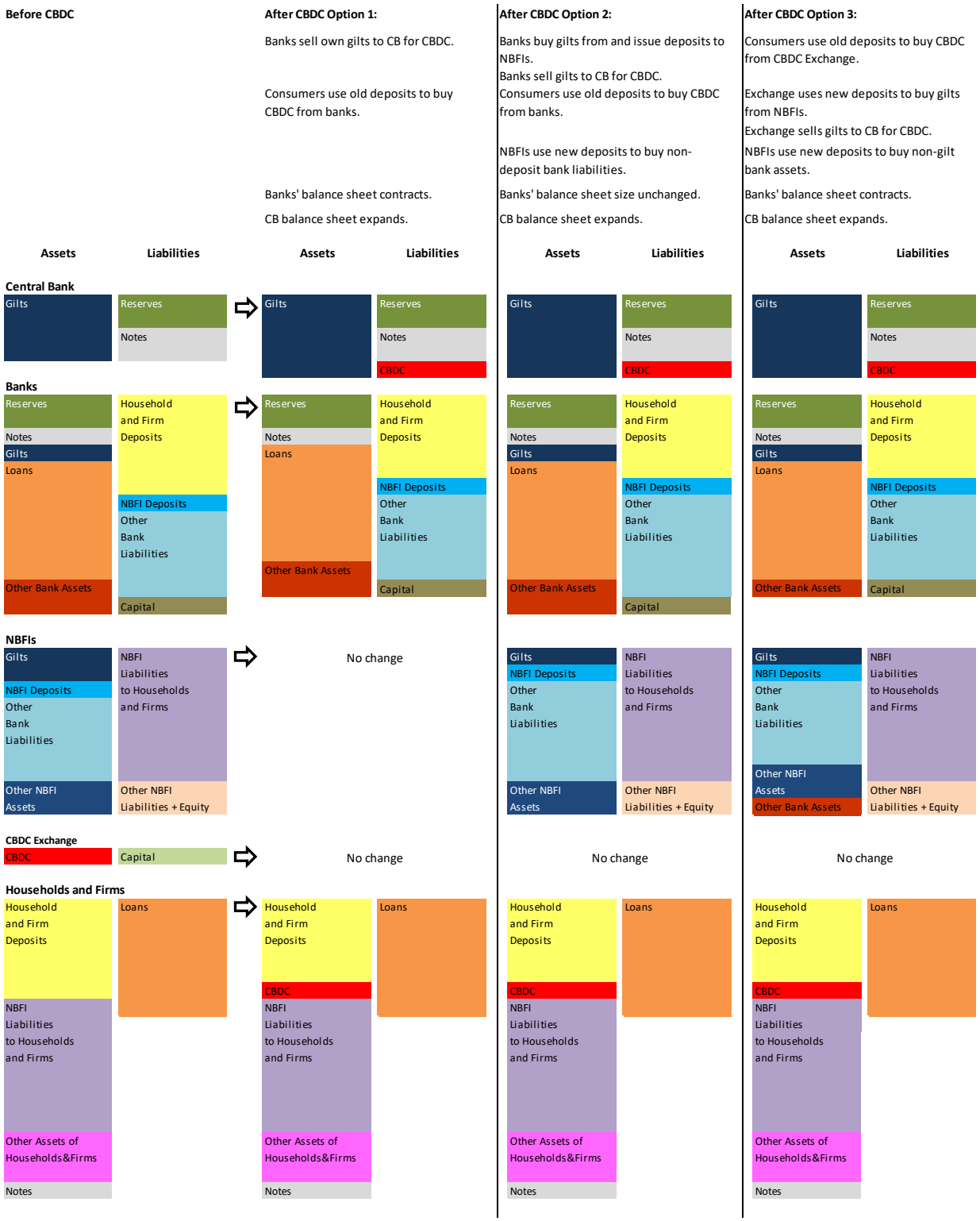

Figure 9. Model FI+ – Map

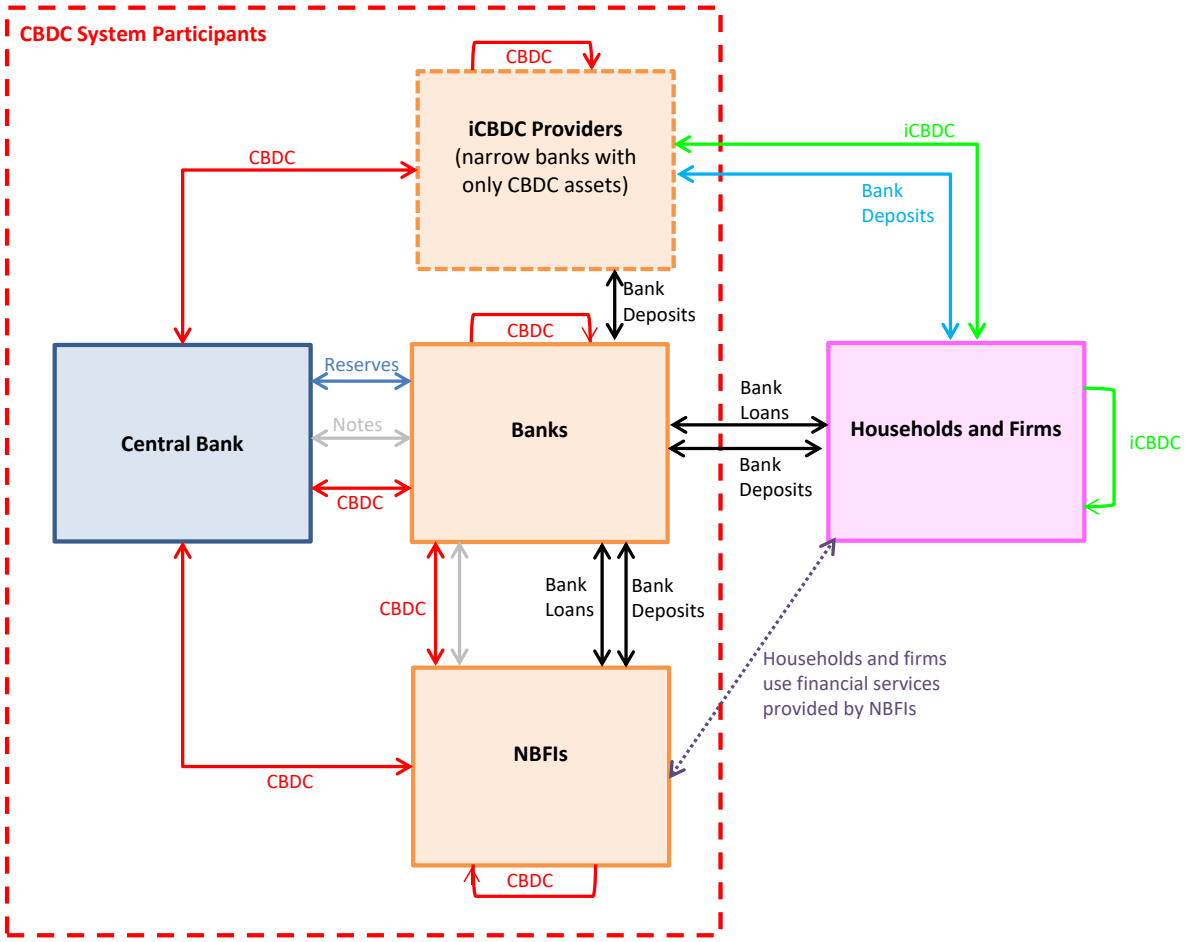

Figure 10. Model FI+ – Households and Firms Switch from Deposits to iCBDC

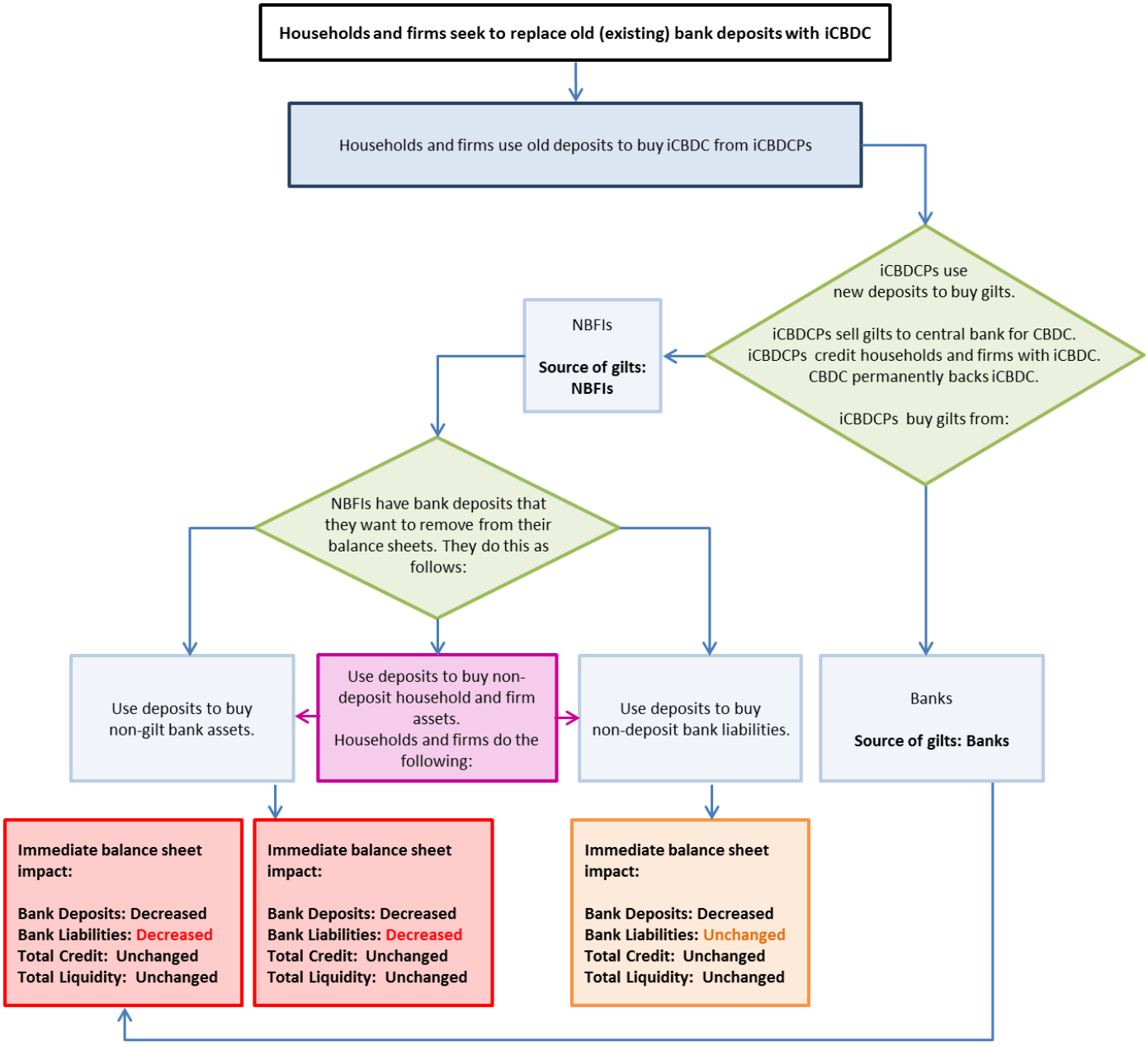

Figure 11. Model FI+ – Impact of Households and Firms Replacing Deposits with iCBDC

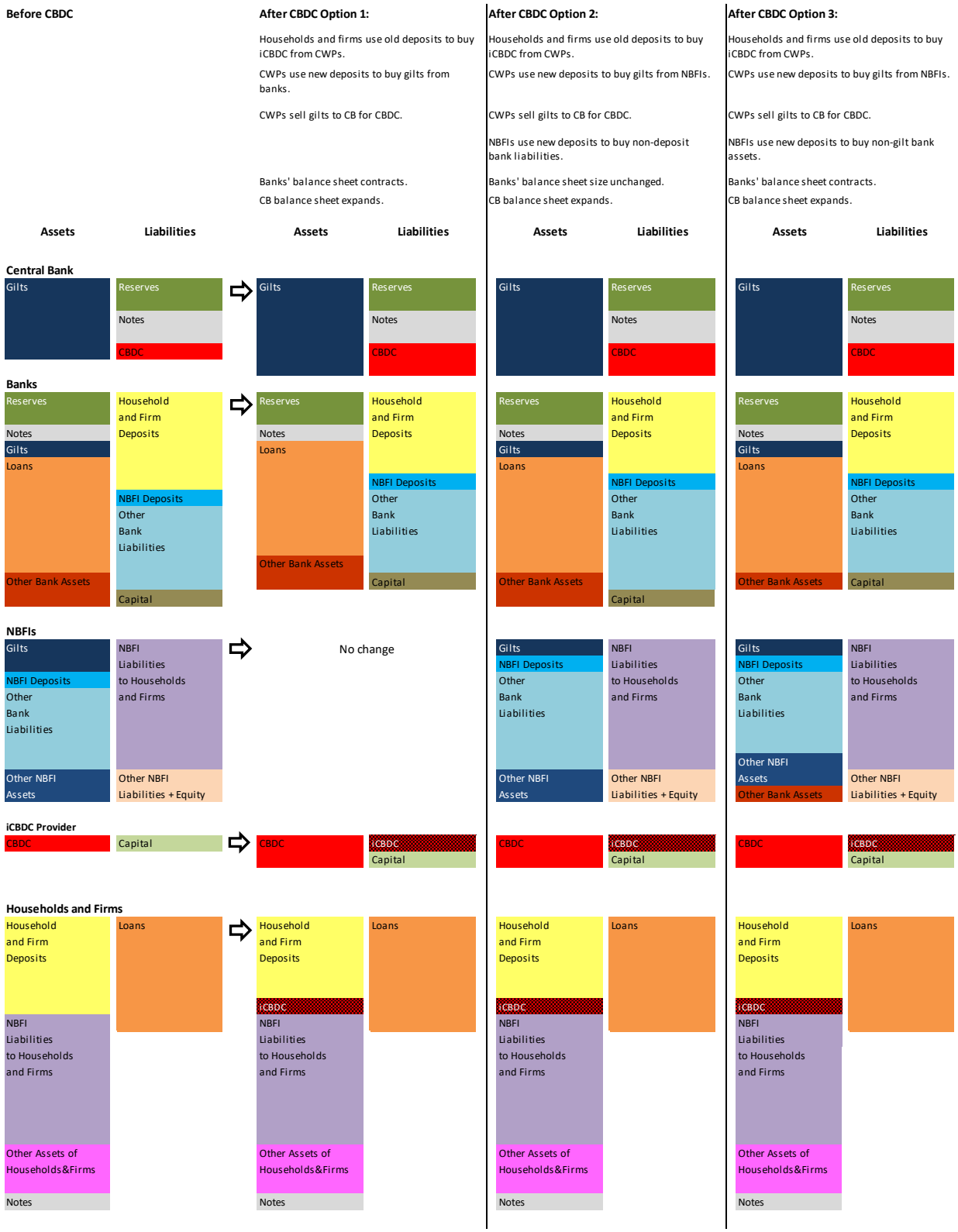

Figure 12. Illustration of the Operation of a CBDC Exchange