Liquidity regulation and the implementation of monetary policy*

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Abstract

In addition to revamping existing rules for bank capital, Basel III introduces a new global framework for liquidity regulation. One part of this framework is the liquidity coverage ratio (LCR), which requires banks to hold sufficient high-quality liquid assets to survive a 30-day period of market stress. As monetary policy typically involves targeting the interest rate on loans of one of these assets – central bank reserves – it is important to understand how this regulation may impact the efficacy of central banks' current operational frameworks. We introduce term funding and an LCR requirement into an otherwise standard model of monetary policy implementation. We show that when banks face the possibility of an LCR shortfall, it becomes more challenging for a central bank to control the overnight interest rate and the short end of the yield curve becomes steeper. Our results suggest that central banks may want to adjust their operational frameworks as the new regulation is implemented.

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1 Introduction

In response to the recent global financial crisis, the Basel Committee on Banking Supervision (BCBS) announced a new international regulatory framework for banks, known as Basel III. In addition to revamping the existing capital rules, Basel III introduces – for the first time – a global framework for liquidity regulation. The new regulation prescribes two separate, but complementary, minimum standards for managing liquidity risk: the *liquidity coverage ratio* (LCR) and the *net stable funding ratio* (NSFR). These standards aim to ensure that banks hold a more liquid portfolio of assets and better manage the maturity mismatch between their assets and liabilities. Specifically, the LCR requires each bank to hold a sufficient quantity of highly-liquid assets to survive a 30-day period of market stress. The NSFR focuses on a one-year time horizon and establishes a minimum amount of stable funding each bank must obtain based on the liquidity characteristics of its assets and activities. Implementation of the LCR and the NSFR is scheduled to begin in January 2015 and January 2018, respectively.[1]

How might these new liquidity regulations affect the process through which central banks implement monetary policy? In many jurisdictions, this process involves setting a target for the interest rate at which banks lend central bank reserves to one another, typically overnight and on an unsecured basis. Because these reserves are part of banks' portfolio of highly-liquid assets, the regulations will potentially alter behavior in the interbank market, changing the relationship between market conditions and the resulting interest rate. In addition, monetary policy operations will influence banks' regulatory liquidity ratios and, hence, may affect their compliance with the new liquidity standards, at least at the margin. These linkages suggest that the new regulations may have subtle and unintended consequences that could potentially reduce the effectiveness of central banks' current operating procedures.

We extend a standard model of banks' reserve management and interbank lending to study how the introduction of an LCR requirement affects the process of implementing monetary policy in a

[1] The LCR requirement will be phased in gradually, beginning at 60% coverage in January 2015 and rising 10 percentage points each year to reach 100% in January 2019.

corridor system. While there has been some discussion of this topic,[2] ours is the first model that can be used to analyze these issues systematically. We show that when banks face the possibility of an LCR shortfall, the relationship between the quantity of central bank reserves and market interest rates can change dramatically. A bank that is concerned about possibly violating the LCR has a stronger incentive to seek term funding in the market and is more likely to borrow from the central bank's standing facility. Both of these actions add to the bank's reserve holdings and thus lower the need to seek funds in the overnight market to ensure the bank's reserve requirement is met. This lower demand for overnight funds tends to drive down the overnight rate, whereas the increased demand for term funding tends to make the short end of the yield curve steeper.

We also study a central bank's ability to control interest rates through open market operations. We look at operations that differ along several dimensions: the types of assets used in the operation, the types of counterparties, and outright versus reverse operations. In the standard model with no LCR requirement, the overnight interest rate is determined by the total quantity of reserves supplied by the central bank; the type of operation used to create these reserves is irrelevant. We show that once an LCR requirement is introduced, this result no longer holds. In our model, the structure of an open market operation determines its effects on bank balance sheets and, hence, the likelihood that individual banks may face an LCR deficiency. This likelihood, in turn, affects banks' incentives to trade in interbank markets. As a result, the impact of an operation on equilibrium interest rates can be quite sensitive to the way it is structured. For example, in some cases the overnight rate is more responsive to changes in the supply of reserves than in the standard model, while in other cases it becomes completely unresponsive. In some cases the yield curve tends to steepen when the central bank adds reserves, while in others it steepens when reserves are removed. The size of these effects depends on a variety of factors, including the liquidity surplus/deficit of the banking system and the specific parameters used in calculating the LCR requirement.

The LCR rules were first published in December 2010, but were subsequently revised in January 2013. Our model shows how the revised rules mitigate – but do not eliminate – the regulation's impact on monetary policy implementation. Overall, our results indicate that central banks may

[2] See, for example, Bindseil and Lamoot (2011) and Schmidt (2012). Bonner and Eijffinger (2013) study empirically the impact of the quantitative liquidity requirement introduced in Holland in 2003 on money markets there.

wish to adjust their operational frameworks for implementing monetary policy when the LCR is introduced. At a minimum, they will need to monitor developments that materially affect the LCR of the banking system, in much the same way as they have traditionally monitored other factors that affect interbank markets.

We briefly review the LCR regulation in the next section before presenting our model in Section 3. We derive banks' demand for overnight and term interbank loans as well as the equilibrium interest rates on these loans in Section 4, while in Section 5 we study the central bank's ability to control interest rates using open market operations. Section 6 examines the importance of the treatment of central bank loans in the LCR calculation and discusses the impact of the revised LCR rules. Section 7 concludes with a discussion of policy options.

2 The liquidity coverage ratio (LCR)

The liquidity coverage ratio is calculated by dividing a bank's stock of unencumbered high-quality liquid assets (HQLA) by its projected net cash outflows over a 30-day horizon under a stress scenario specified by supervisors. The new regulation requires this ratio to be at least one, that is,

$$LCR = \frac{\textit{Stock of unencumbered high-quality liquid assets}}{\textit{Total net cash outflows over the next 30 calendar days}} \geq 1. \quad (1)$$

Two types (or "levels") of assets can be applied toward the HQLA pool. Level 1 assets include cash, central bank reserves and certain marketable securities backed by sovereigns and central banks.[3] Level 2 assets are divided into two subgroups: Level 2A assets include certain government securities, corporate debt securities and covered bonds, while Level 2B assets include lower-rated corporate bonds, residential mortgage backed securities and equities that meet certain conditions. Level 2A assets can account for a maximum of 40% of a bank's total stock of HQLA, whereas Level 2B assets can account for a maximum of 15% of the total.

[3]Central bank reserves held to meet reserve requirements may be included in the calculation of HQLA under some conditions. Specifically, BCBS (2013) states that "[l]ocal supervisors should discuss and agree with the relevant central bank the extent to which central bank reserves should count towards the stock of liquid assets, i.e., the extent to which reserves are able to be drawn down in times of stress".

The denominator of the LCR, projected net cash outflows, is calculated by multiplying the size of various types of liabilities and off-balance sheet commitments by the rates at which they are expected to run off or be drawn down in the stress scenario. This scenario includes a partial loss of retail deposits, significant loss of unsecured and secured wholesale funding, contractual outflows from derivative positions associated with a three-notch ratings downgrade, and substantial calls on off-balance sheet exposures. The calibration of scenario run-off rates reflects a combination of the experience during the recent financial crisis, internal stress scenarios of banks, and existing regulatory and supervisory standards. From these outflows, banks are permitted to subtract expected inflows for 30 calendar days into the future. To prevent banks from relying solely on anticipated inflows to meet their liquidity requirement, and to ensure a minimum level of liquid asset holdings, the fraction of outflows that can be offset this way is capped at 75%.

Once the LCR has been fully implemented, its 100% threshold will be a minimum requirement in normal times. During a period of stress, however, banks would be expected to use their pool of liquid assets, thereby temporarily falling below the required level. Our focus in this paper is on the process of implementing monetary policy in normal times, when banks are expected to fully meet the requirement.

3 The model

Our analysis is based on a model of monetary policy implementation in the tradition of Poole (1968).[4] Banks raise capital and issue deposits while holding loans, bonds and reserves as assets. They can borrow and lend funds in interbank markets for overnight and term loans, and they are subject to both a reserve requirement and the LCR requirement discussed above. The central bank influences activity in interbank markets using a combination of open market operations and standing facilities where banks can deposit surplus funds or borrow against collateral.

[4] Contributions to this literature include Dotsey (1991), Clouse and Dow (1999, 2002), Guthrie and Wright (2000), Bartolini, Bertola and Prati (2002), Bindseil (2004), Whitesell (2006), Ennis and Weinberg (2007), Ennis and Keister (2008), Bech and Klee (2011), and Afonso and Lagos (2012), among others.

3.1 Balance sheets and payment shocks

There is a continuum of banks, indexed by $i \in [0,1]$, each of which is a price-taker in interbank markets and aims to maximize expected profits. Bank i enters these markets with a balance sheet of the following form:

Assets		Liabilities	
Loans	L^i	Deposits	D^i
Bonds	B^i		
Reserves	R^i	Equity	E^i

(2)

The values of these variables are determined in part by activities that are outside of the scope of the model, such as the bank's activity on behalf of customers, and in part by the central bank's open market operations, which we discuss in Section 5. For the moment, we take these values as given and ask how equilibrium interest rates depend on the properties of bank balance sheets.

There are markets for two types of interbank loans: overnight and term. Term loans have a duration longer than 30 days, which implies they are treated differently from overnight loans for LCR purposes. Let Δ^i and Δ_T^i denote the amounts bank i borrows in the overnight and term market, respectively; negative values of these variables correspond to lending. The bank's balance sheet after the interbank markets close is:

Assets		Liabilities	
Loans	L^i	Deposits	D^i
Bonds	B^i	Net interbank borrowing	$\Delta^i + \Delta_T^i$
Reserves	$R^i + \Delta^i + \Delta_T^i$	Equity	E^i

The liability side now has a new category, "net interbank borrowing," which is the counterpart to the inflow of reserves from trading in the interbank market. Note that net interbank borrowing can be either positive or negative, and hence $\Delta^i + \Delta_T^i$ can either be a liability (as depicted above) or an asset (i.e., a claim on other banks).

After the interbank market has closed, the bank experiences a payment shock in which an amount ε^i of customer deposits is sent as a payment to another bank. If ε^i is negative, the shock represents an unexpected inflow of funds. The value of ε^i for each bank is drawn from a common, symmetric distribution G with density function g and with zero mean. The assumption that the interbank market closes before these payment shocks are realized is a standard way of capturing the imperfections in interbank markets that prevent banks from being able to exactly target their end-of-day reserve balance.[5] Depending on the size of its payment shock, the bank may need to borrow from the central bank at the end of the day to meet its regulatory requirements. Let $X^i \geq 0$ denote the amount borrowed by bank i. The bank pledges loans to the central bank as collateral; letting β denote the haircut required by the central bank, bank i's end-of-day balance sheet is then:

Assets		Liabilities	
Loans	L^i	Deposits	$D^i - \varepsilon^i$
- hereof encumbered	$X^i/(1-\beta)$	Net interbank borrowing	$\Delta^i + \Delta^i_T$
Bonds	B^i	Central bank borrowing	X^i
Reserves	$R^i + \Delta^i + \Delta^i_T - \varepsilon^i + X^i$	Equity	E^i

We now discuss the two regulatory requirements and how they determine the value of X^i.

3.2 The reserve requirement

Each bank faces a reserve requirement of the form

$$R^i + \Delta^i + \Delta^i_T - \varepsilon^i + X^i \geq K^i. \tag{3}$$

The left-hand side of this expression is the bank's reserve holdings at the end of the day, taking into account funds borrowed/lent in the interbank markets, the payment shock, and borrowing from the central bank. The right-hand side is the requirement for the day, which we can think of as being determined by past values of items on the bank's balance sheet (such as deposits), but is a fixed number when the day begins. If the bank would violate this requirement after the realization of

[5] Ennis and Weinberg (2012) and Afonso and Lagos (2012) study models with explicit trading frictions and derive how a bank's end-of-day balance depends, in part, on the trading opportunities that arise. Extending our analysis in this direction is a promising avenue for future research, as it would allow one to study how the LCR requirement affects features of the market that our Walrasian approach is not designed to address, such as the dispersion of interest rates across transactions and over time.

the payment shock, it must borrow funds from the central bank to ensure that (3) holds.

Borrowing from the central bank is costly and, therefore, each bank will borrow the minimum amount needed to meet its regulatory requirements. Let X_K^i denote the minimum amount bank i must borrow to fulfill the reserve requirement in (3), that is,

$$X_K^i = \max\left\{\varepsilon^i + K^i - R^i - \Delta^i - \Delta_T^i, 0\right\}. \tag{4}$$

3.3 The LCR requirement

In the context of our model, bank i's LCR requirement is

$$LCR^i = \frac{B^i + R^i + \Delta^i + \Delta_T^i - \varepsilon^i + X^i}{\theta_D(D^i - \varepsilon^i) + \Delta^i + \theta_X X^i} \geq 1. \tag{5}$$

Recall from (1) that the numerator of the ratio is the total value of the bank's high-quality liquid assets, which here simply equals its end-of-day holdings of bonds plus reserves.[6] The denominator measures the 30-day net cash outflow assumed under the stress scenario, which includes the run-off of deposits at rate θ_D, of overnight interbank loans at 100%, and of loans from the central bank at rate θ_X. The LCR rules allow a run-off rate on (secured) loans from the central bank of 0% but, as these rules are a minimum standard, local authorities can set a higher value of θ_X at their discretion. Terms loans expire outside the duration of the stress scenario and hence do not enter the denominator of the ratio.[7]

Let X_C^i denote the minimum amount bank i must borrow from the central bank to fulfill the LCR requirement in (5), that is,

$$X_C^i = \max\left\{\frac{(1-\theta_D)\varepsilon^i - C^i - R^i - \Delta_T^i}{1-\theta_X}, 0\right\}, \tag{6}$$

where

$$C^i \equiv B^i - \theta_D D^i$$

[6]For simplicity, we assume that reserves held to meet reserve requirements are included in the calculation of high-quality liquid assets. It is straightforward to modify the model to exclude these balances.

[7]The regulation divides retail deposits into two categories: "stable" and "less stable". Stable retail deposits are those covered by an effective deposit insurance scheme as defined in the LCR rules text and are assigned a minimum run-off rate of 5%. Less stable retail deposits are assigned a minimum run-off rate of 10%. If the deposit insurance scheme meets certain additional criteria, the run-off rate for stable deposits can be lowered to 3%. See BCBS (2013) for more detail.

represents the bank's surplus (or shortfall, if negative) of liquid assets for LCR purposes before reserve holdings are taken into account.

3.4 Borrowing from the central bank

Combining equations (4) and (6), the minimum amount bank i must borrow from the central bank's lending facility to meet both its reserve and LCR requirements is given by

$$\begin{aligned} X^i &= \max\left\{X_K^i, X_C^i\right\} \qquad (7) \\ &= \max\left\{\varepsilon^i + K^i - R^i - \Delta^i - \Delta_T^i, \frac{(1-\theta_D)\varepsilon^i - C^i - R^i - \Delta_T^i}{1-\theta_X}, 0\right\}. \end{aligned}$$

Figure 1 depicts X^i as a function of the realized payment shock ε^i together with a density function g for this shock. The figure is drawn assuming the runoff rates in the denominator of the LCR satisfy $\theta_X < \theta_D$; the reverse case is presented in Figure 5 in Appendix B. The blue line in each panel represents equation (4), borrowing needed to satisfy the reserve requirement. The critical value of the payment shock above which this component of borrowing is positive is

$$\varepsilon_K^i \equiv R^i + \Delta^i + \Delta_T^i - K^i. \qquad (8)$$

(a) $\varepsilon_K^i < \varepsilon_C^i$ (b) $\varepsilon_K^i > \varepsilon_C^i$

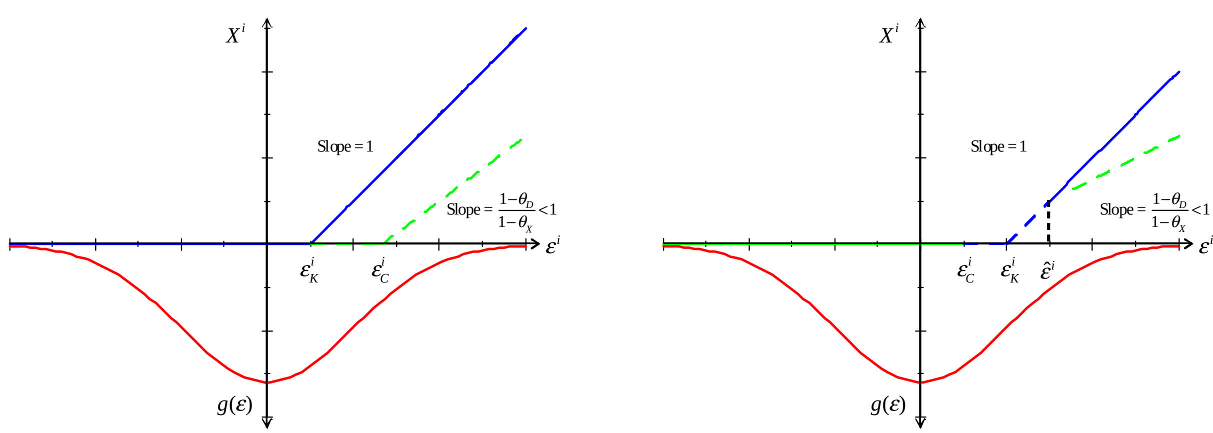


Figure 1: Bank i's borrowing from the central bank lending facility (with $\theta_X < \theta_D$)

The green line represents equation (6), borrowing needed to satisfy the LCR requirement. The critical value for this case is

$$\varepsilon_C^i \equiv \frac{C^i + R^i + \Delta_T^i}{1-\theta_D}. \tag{9}$$

The bank's borrowing X^i is the upper envelope of these two lines. Note that the critical values $\left(\varepsilon_K^i, \varepsilon_C^i\right)$ are determined, in part, by the bank's trading behavior $\left(\Delta^i, \Delta_T^i\right)$.

As the figure shows, two distinct cases arise. In panel (a), the values $\left(\Delta^i, \Delta_T^i\right)$ are such that $\varepsilon_K^i < \varepsilon_C^i$ holds. In this case, the amount borrowed from the central bank's lending facility is always determined by the bank's need to meet its reserve requirement; the LCR requirement is never a binding concern. To see this, note that if ε^i is greater than ε_K^i, the bank will have a deficiency in its reserve requirement and will borrow just enough from the central bank to correct this deficiency. The figure shows that this borrowing will always be sufficient to ensure that the bank also satisfies its LCR requirement, even when the shock ε^i is greater than ε_C^i.

The relationship is different in panel (b) of the figure, where the values $\left(\Delta^i, \Delta_T^i\right)$ are such that $\varepsilon_K^i > \varepsilon_C^i$ holds. In this case, the amount borrowed from the central bank can be determined by either of the two requirements, depending on the realized value of ε^i. In particular, the amount borrowed is determined by the LCR requirement for values of ε^i in the interval $[\varepsilon_C^i, \hat{\varepsilon}^i]$, where

$$\hat{\varepsilon}^i \equiv \frac{C^i + (1-\theta_X)\left(K^i - \Delta^i\right) + \theta_X\left(R^i + \Delta_T^i\right)}{\theta_X - \theta_D}, \tag{10}$$

and by the reserve requirement when ε^i is greater than $\hat{\varepsilon}^i$.

3.5 Profits

The bank earns the interest rates r_L and r_B on its loans and bonds, respectively. It pays an interest rate r_D on customer deposits and pays (or earns) r and r_T on its interbank borrowing (or lending) in each market. The bank earns r_K on balances held at the central bank to meet its reserve requirement and r_R on any excess balances. In addition, the bank faces a penalty rate $r_X > r_R$ (including the value of any associated stigma effects)[8] for funds borrowed from the central bank's

[8] See Ennis and Weinberg (2012) and Armantier et al. (2011) for studies of the potential for stigma to be associated with borrowing from the central bank.

lending facility. Bank i's realized profit for the period can, therefore, be written as

$$\begin{aligned}\pi^i(\varepsilon^i) &= r_L L^i + r_B B^i - r_D\left(D^i - \varepsilon^i\right) - r\Delta^i - r_T\Delta_T^i + r_K K^i \\ &\quad + r_R \max\left\{R^i + \Delta^i + \Delta_T^i + X^i - \varepsilon^i - K^i, 0\right\} - r_X X^i.\end{aligned}$$

Using (7) and $E\left[\varepsilon^i\right] = 0$, and rearranging terms, we can write the expected value of bank i's profit before its payment shock is realized as

$$\begin{aligned}E[\pi^i] &= r_L L^i + r_B B^i - r_D D^i + r_K K^i - r\Delta^i - r_T\Delta_T^i + r_R\left(R^i + \Delta^i + \Delta_T^i - K^i\right) \\ &\quad -(r_X - r_R)E\left[\max\left\{\varepsilon^i + K^i - R^i - \Delta^i - \Delta_T^i, \frac{(1-\theta_D)\varepsilon^i - C^i - R^i - \Delta_T^i}{1-\theta_X}, 0\right\}\right].\end{aligned} \tag{11}$$

3.6 Discussion

Our model represents a minimal departure from the standard framework that can address issues related to the LCR and its effect on both overnight and term interest rates. By studying a one-period setting, we are necessarily abstracting from the factors that usually generate term premia, including changes in future overnight interest rates, additional liquidity and credit risk, etc. This approach allows us to focus directly on the effects of the liquidity regulation itself. Because the only difference between overnight and term loans in our model is their treatment in the LCR calculation, any term premium that arises in equilibrium is necessarily a result of the regulation.

At the same time, our model is sufficiently general to represent various types of operating frameworks used in practice to implement monetary policy. A standard corridor framework, for example, corresponds to situation where the central bank sets the interest rate r_X at its lending facility above its target rate and the interest rate r_R paid on excess reserves below the target. The floor system of monetary policy implementation, in contrast, involves setting r_R equal to the target rate.[9] The model could also represent an operational framework with no reserve requirement by setting K to zero, in which case condition (3) simply requires that a bank not end the day with an overdraft in its reserve account. For operating frameworks that allow reserve averaging, this model can be thought of as representing either the final day of a reserve maintenance period or the

[9]See Goodfriend (2002) and Keister, Martin, and McAndrews (2008) for discussions of the floor system of monetary policy implementation.

average values over the entire period.[10]

4 Equilibrium

In this section, we derive each bank's demand for funds in the two interbank markets, aggregate these demands across banks, and derive the equilibrium interest rates. We focus on the case where $\theta_X < \theta_D$; the corresponding analysis for the reverse case is contained in Appendix B.

4.1 The demand for interbank loans

Bank i will choose its interbank borrowing activity $\left(\Delta^i, \Delta_T^i\right)$ to maximize its expected profit (11). Dropping terms that do not depend on the bank's choices of Δ^i and Δ_T^i, the maximization problem can be written as

$$\max_{\left(\Delta^i, \Delta_T^i\right)} -r\Delta^i - r_T\Delta_T^i + r_R\left(R^i + \Delta^i + \Delta_T^i - K^i\right) \tag{12}$$
$$-(r_X - r_R)\left\{\begin{array}{c} \mathbb{I}_{\left(\varepsilon_C^i < \varepsilon_K^i\right)} \int_{\varepsilon_C^i}^{\hat{\varepsilon}^i} \left(\frac{(1-\theta_D)\varepsilon^i - C^i - R^i - \Delta_T^i}{1-\theta_X}\right) g\left(\varepsilon^i\right) d\varepsilon^i \\ + \int_{\max\{\varepsilon_K^i, \hat{\varepsilon}^i\}}^{\infty} \left(\varepsilon^i + K^i - R^i - \Delta^i - \Delta_T^i\right) g\left(\varepsilon^i\right) d\varepsilon^i \end{array}\right\},$$

where the indicator function $\mathbb{I}$ takes the value one if the expression in parentheses is true and zero otherwise. The solution to this problem is characterized in the following proposition, a proof of which is provided in Appendix A.

Proposition 1 *Suppose $\theta_X < \theta_D$. If $r_T > r$, bank i will choose $\left(\Delta^i, \Delta_T^i\right)$ so that the critical values $\left(\varepsilon_K^i, \varepsilon_C^i, \hat{\varepsilon}^i\right)$ defined in (8) – (10) satisfy*

$$r = r_R + (r_X - r_R)\left(1 - G\left[\hat{\varepsilon}^i\right]\right) \quad \textit{and} \tag{13}$$

$$r_T = r + \frac{r_X - r_R}{1-\theta_X}\left(G\left[\hat{\varepsilon}^i\right] - G\left[\varepsilon_C^i\right]\right). \tag{14}$$

If $r_T = r$, the bank will choose $\left(\Delta^i, \Delta_T^i\right)$ so that these values satisfy

$$\varepsilon_C^i \geq \varepsilon_K^i \quad \textit{and} \quad r = r_R + (r_X - r_R)\left(1 - G\left[\varepsilon_K^i\right]\right). \tag{15}$$

[10] The type of framework studied here can be extended to include reserve averaging as shown by Clouse and Dow (1999), Bartolini, Bertola, and Prati (2002), Whitesell (2006), Ennis and Keister (2008), and others.

When the term interest rate is higher than the overnight rate, equations (13) and (14) together imply that the bank will choose $\left(\Delta^i, \Delta_T^i\right)$ so that $\hat{\varepsilon}^i > \varepsilon_C^i$ holds, as depicted in panel (b) of Figure 1. Equation (13) then states that the bank will equate its expected marginal value of overnight funds to the market interest rate r. The expression for this marginal value can be understood by considering the benefit of an extra dollar borrowed in the overnight market for each possible realization of the bank's payment shock. If ε^i is below ε_C^i, the bank will satisfy its regulatory requirements without borrowing from the central bank and the extra dollar will simply earn the interest rate on excess reserves r_R. If ε^i is between ε_C^i and $\hat{\varepsilon}^i$, the amount the bank borrows from the central bank will be determined by its need to satisfy the LCR requirement, which is not affected by this extra dollar of overnight borrowing. In this case, the benefit of holding the dollar will again be the interest rate r_R it earns as excess reserves. If ε^i is above $\hat{\varepsilon}^i$, however, the bank will borrow just enough from the central bank to meet its reserve requirement. In this case, the additional dollar will allow the bank to borrow one dollar less from the central bank, saving it the penalty rate r_X. The expected value of an additional dollar of overnight funding is, therefore,

$$r_R \cdot \text{prob}[\varepsilon^i \leq \hat{\varepsilon}^i] + r_X \cdot \text{prob}[\varepsilon^i > \hat{\varepsilon}^i].$$

Using the distribution function G to determine these probabilities and rearranging terms yields the right-hand side of equation (13).

Similarly, equation (14) states that the bank will equate its marginal value of term funds to the interest rate r_T in the term market. The benefit of borrowing an additional dollar of term funds also depends on the realized value of the bank's payment shock. If ε^i is smaller than ε_C^i, the bank has no need to borrow from the central bank and the extra dollar will earn the interest rate on excess reserves r_R. If ε^i is larger than $\hat{\varepsilon}^i$, the extra dollar of term borrowing will lower the amount the bank needs to borrow from the central bank to meet its reserve requirement, just like an extra dollar of overnight borrowing would, saving the bank the penalty rate r_X. The added benefit of term borrowing comes when ε^i falls between ε_C^i and $\hat{\varepsilon}^i$. In this case, an extra dollar of term funding decreases the amount the bank needs to borrow from the central bank to meet its LCR requirement by $(1-\theta_X)^{-1} \geq 1$ dollars. Note that if the runoff rate θ_X is positive, one dollar of term borrowing will lower the bank's need to borrow from the central bank by more than one dollar in this situation. The expected value of an additional dollar of term funding thus equals the expected value of an additional dollar of overnight funding plus an extra term

$$\frac{r_X - r_R}{1-\theta_X} \cdot \text{prob}[\varepsilon_C^i < \varepsilon^i \leq \hat{\varepsilon}^i],$$

which together yield the right-hand side of (14).

When the term and overnight interest rates are equal, the bank can increase its LCR at no cost by borrowing at term and lending the same amount of funds out overnight. The first component of equation (15) states that, in this case, the bank will choose $\left(\Delta^i, \Delta_T^i\right)$ so that $\varepsilon_C^i \geq \varepsilon_K^i$ holds, as in panel (a) of Figure 1, and the LCR requirement is never a binding concern. The second component says that the bank's marginal value of funds again equals the interest rate on excess reserves r_R plus the expected benefit of an extra dollar of reserves in meeting the reserve requirement. The bank will equate this marginal value to the market interest rate r. Note that many pairs $\left(\Delta^i, \Delta_T^i\right)$ will satisfy the two conditions in equation (15) and the bank will be indifferent between any of these actions.

4.2 Aggregation

An immediate implication of Proposition 1 is that all banks will choose their interbank activity $\left(\Delta^i, \Delta_T^i\right)$ to generate the same critical values $\left(\varepsilon_K^i, \varepsilon_C^i, \hat{\varepsilon}^i\right)$. Bank i's actual trading activity will depend on the specifics of its initial balance sheet (2) but, once this activity has taken place, each bank will face the same probability of a deficiency in its reserve requirement and in its LCR requirement. In what follows, therefore, we drop the i superscript from these critical values and simply write $(\varepsilon_K, \varepsilon_C, \hat{\varepsilon})$. Given the critical values determined by the proposition, bank i's optimal trading behavior is

$$\begin{aligned} \Delta^i &= K^i + C^i + \varepsilon_K - (1-\theta_D)\,\varepsilon_C \quad \text{and} \\ \Delta_T^i &= -C^i - R^i + (1-\theta_D)\,\varepsilon_C. \end{aligned}$$

The total demand for borrowing in the overnight interbank market can be determined by integrating the individual demands for each bank,

$$\Delta \equiv \int_0^1 \Delta^i di = \int_0^1 K^i di + \int_0^1 C^i di + \varepsilon_K - (1-\theta_D)\,\varepsilon_C.$$

Similarly, the total demand for term interbank borrowing is given by

$$\Delta_T \equiv \int_0^1 \Delta_T^i di = -\int_0^1 C^i di - \int_0^1 R^i di + (1-\theta_D)\,\varepsilon_C.$$

Letting K, C, and R denote the aggregate values of required reserves, the LCR surplus (net of reserves), and reserve holdings, respectively, we can write these equations as

$$\begin{aligned} \Delta &= K + C + \varepsilon_K - (1-\theta_D)\,\varepsilon_C \quad \text{and} \\ \Delta_T &= -C - R + (1-\theta_D)\,\varepsilon_C. \end{aligned}$$

These two equations demonstrate that the net demand for borrowing in each market depends only on the *aggregate* balance sheet of the banking system. While an individual bank's demand for funds will depend on its own balance sheet characteristics (2), the aggregate demand for funds does not depend on how these characteristics are distributed across banks.

4.3 Equilibrium interest rates

Since every interbank loan involves one bank borrowing funds and another bank lending, market clearing requires that the net quantity of lending in each market be zero, that is,

$$\Delta = \Delta_T = 0.$$

Using these two equilibrium conditions together with Proposition 1, we can derive the equilibrium interest rates (r^*, r_T^*) as functions of the elements of the aggregate balance sheet of the banking system. In equilibrium, the critical values (8) – (10) are given by

$$\varepsilon_K^* \equiv R - K, \quad \varepsilon_C^* \equiv \frac{R+C}{1-\theta_D}, \quad \text{and} \quad \hat{\varepsilon}^* \equiv \frac{C + (1-\theta_X)\,K + \theta_X R}{\theta_X - \theta_D}. \tag{16}$$

Substituting these expressions into the demand functions from Proposition 1 yields the equilibrium pricing relationships.

Proposition 2 *When $\theta_X < \theta_D$, the equilibrium interest rates are given by*

$$r^* = r_R + (r_X - r_R)\left(1 - G\left[\max\left\{\hat{\varepsilon}^*, \varepsilon_K^*\right\}\right]\right) \quad \textit{and} \tag{17}$$

$$r_T^* = r^* + \frac{r_X - r_R}{1-\theta_X}\max\left\{G\left[\hat{\varepsilon}^*\right] - G\left[\varepsilon_C^*\right], 0\right\}. \tag{18}$$

This result establishes how the supply of reserves R and other elements of the aggregate balance sheet of the banking system affect equilibrium interest rates. This balance sheet determines the equilibrium critical values $(\varepsilon_K^*, \varepsilon_C^*, \hat{\varepsilon}^*)$ through the relationships in (16) and then Proposition 2 uses these critical values to determine r^* and r_T^*. Equation (17) shows that the equilibrium overnight rate equals the interest rate paid on excess reserves r_R plus a spread that reflects the marginal value of overnight funds in avoiding a potential deficiency in the reserve requirement, which is common to all banks in equilibrium. Similarly, equation (18) shows that the equilibrium term interest rate equals the overnight rate plus a term premium that reflects the marginal value of term funding to banks in avoiding a potential deficiency in the LCR requirement.

Using the fact that G is a probability distribution function whose value is always in $[0,1]$, Proposition 2 allows us to place upper and lower bounds on each rate. In addition, equation (18) shows that the equilibrium term premium is always non-negative.

Corollary 1 *The equilibrium interest rates satisfy $r^* \in [r_R, r_X]$ and $r_T^* \in \left[r_R, \frac{r_X - \theta_X r_R}{1-\theta_X}\right]$ and the equilibrium term premium $(r_T^* - r^*)$ is non-negative.*

As is standard, the overnight rate lies in the corridor formed by the interest rate on excess reserves r_R and the all-in cost of borrowing from the central bank r_X. If the run-off rate θ_X on loans from the central bank is positive, the upper bound on the term rate is higher than r_X, reflecting the fact that a dollar of term borrowing may save the bank from having to borrow more than a dollar from the central bank.[11]

If the LCR is never a binding concern for banks, our results are equivalent to those from a standard Poole-type model. The next corollary demonstrates this fact by giving a precise condition under which the equilibrium overnight rate is the same as would arise in a model with no LCR

[11] While Propositon 2 only applies when $\theta_X < \theta_D$, it can be combined with Proposition 5 in Appendix B to show that the result in Corollary 1 holds for all $\theta_X \geq 0$.

requirement, which we denote r^P (the "Poole interest rate"). The corollary also shows that, under this condition, the term premium is zero in equilibrium.

Corollary 2 (Poole, 1968) *Suppose $\theta_X < \theta_D$. If $C + (1 - \theta_D) K + \theta_D R \geq 0$, the interest rate in the overnight interbank market is given by*

$$r^* = r_R + (r_X - r_R)(1 - G[\varepsilon_K^*]) \equiv r^P$$

and the term premium is zero, that is, $r_T^* = r^*$.

Recall that $C \equiv B - \theta_D D$ is the liquidity surplus of the banking system, net of reserves, for LCR purposes. When this surplus is sufficiently large, adding an LCR requirement has no effect on equilibrium interest rates. When the surplus is smaller than the bound given in Corollary 2, however, the LCR does impact equilibrium rates. The next corollary documents the direction of these changes: the introduction of an LCR requirement pushes the overnight rate lower and the term rate higher.

Corollary 3 *Suppose $\theta_X < \theta_D$. If $C + (1 - \theta_D) K + \theta_D R < 0$, the equilibrium interest rates satisfy $r^* < r^P$ and $r_T^* > r^P$, which implies that the term premium is strictly positive.*

It bears emphasizing that the source of this term premium is purely regulatory, as our model abstracts from the additional risks normally associated with term lending. The premium here simply reflects the ability of term funding to raise the value of a bank's LCR and thus help it meet its regulatory requirements.[12]

5 Open market operations

We now turn our attention to the impact of open market operations on equilibrium interest rates. In the standard model with no LCR requirement, the equilibrium overnight rate depends on bank balance sheets only through the total quantity of reserves R. The same is true in our model when the

[12]Bonner and Eijffinger (2012) provide evidence that the introduction of a quantitative liquidity requirement in Holland raised the average term premium on unsecured interbank loans with maturities longer than 30 days. Schmitz (2012) also argues that the LCR requirement is likely to increase term premia.

liquidity surplus of the banking system is sufficiently large. Corollary 2 shows that when the LCR is never a binding concern, the only critical value for the payment shock that affects equilibrium interest rates is ε_K^*. As shown in equation (16), the only element of bank balance sheets that affects ε_K^* is the total supply of reserves R. In such settings, one can study how changing R affects equilibrium interest rates without specifying *how* these changes are generated, that is, how the central bank conducts open market operations. In other words, the impact of an open market operation in such settings depends on only on its size – the amount by which it increases or decreases R – and not on what other changes it creates on banks' balance sheets.

When the new liquidity regulations may bind, however, these other balance sheet changes matter because they may alter banks' LCRs and, hence, their incentives in interbank markets. This is an important insight, as open market operations differ in practice both within and across central banks along a number of dimensions. These dimensions include the type of counterparties allowed to participate, the assets eligible as countervalue, and outright versus reverse operations.[13] Within our model, it is possible to vary the central bank's operations in each of these dimensions and study the differing effects on equilibrium interest rates. We focus here on the effects of outright purchases/sales of HQLA (bonds) and of non-HQLA (loans) with banks as counterparties. In appendix D, we study the effects of reverse operations and of operations with non-banks.

The central bank engages in open market operations before the interbank markets open and, hence, the operation is one of the determinants of the bank balance sheets in (2). Let L_0, B_0, R_0, D_0, and E_0 denote the elements of the aggregate balance sheet of the banking system before the operation takes place. Let z denote the quantity of additional reserves created (or removed, if negative) by the operation, so that we have

$$R = R_0 + z.$$

For simplicity, we assume that the central bank perfectly controls the supply of reserves, that is, we

[13] For example, the Federal Reserve distinguishes between *temporary* and *permanent* OMOs. Temporary OMOs involve repurchase and reverse repurchase agreements that are designed to temporarily add to or subtract from the total supply of reserves in the banking system. Permanent OMOs involve the buying and selling of securities outright to permanently add or subtract reserves. The ECB, in contrast, relies to a large extent on revolving reserve operations of various maturities.

abstract from uncertainty about changes in so-called autonomous factors affecting reserves.[14] For each type of operation, we first ask how it affects bank balance sheets, with a particular focus on the resulting LCR of the banking system. We then analyze how the equilibrium interbank interest rates r^* and r_T^* vary with the size of the operation z.

5.1 Operations with banks using HQLA

If the central bank conducts outright purchases of bonds and banks are the sellers of these bonds, the aggregate balance sheet and LCR of the banking system adjust from their initial values as follows:

Assets		Liabilities	
Loans	L_0	Deposits	D_0
Bonds	B_0-z		
Reserves	R_0+z	Equity	E_0

$$\Rightarrow \quad LCR_z = \frac{B_0-z + R_0+z}{\theta_D D_0} = LCR_0$$

Note that both the total size of this balance sheet and the quantity of HQLA held by the banking system are unaffected by the operation, since the newly-created reserves are replacing another Level 1 asset (bonds). The operation also does not change banks' net cash outflows in the 30-day stress scenario. Consequently, the LCR of the banking system is unaffected by this type of operation.[15]

To illustrate the effect of this operation on equilibrium interest rates, we use a numerical example with the following parameter values:

$$r_R = 2\%,\ r_X = 4\%,\ K = 0,\ \theta_D = 10\%,\ \theta_X = 0, \text{ and } \varepsilon^i \sim N(0,1).$$

These values correspond to an operational framework with a corridor width of 200 basis points, no reserve requirements, and the runoff rates θ_D and θ_X set to the minimum standards from BCBS (2013). Furthermore, we set $R_0 = 0$ so that the system begins in a "balanced" situation where

[14] Autonomous factors affect the supply of reserves but do not relate to the use of monetary policy instruments. They include, for example, the quantity banknotes in circulation, government deposits with the central bank, and the net foreign assets of the central bank.

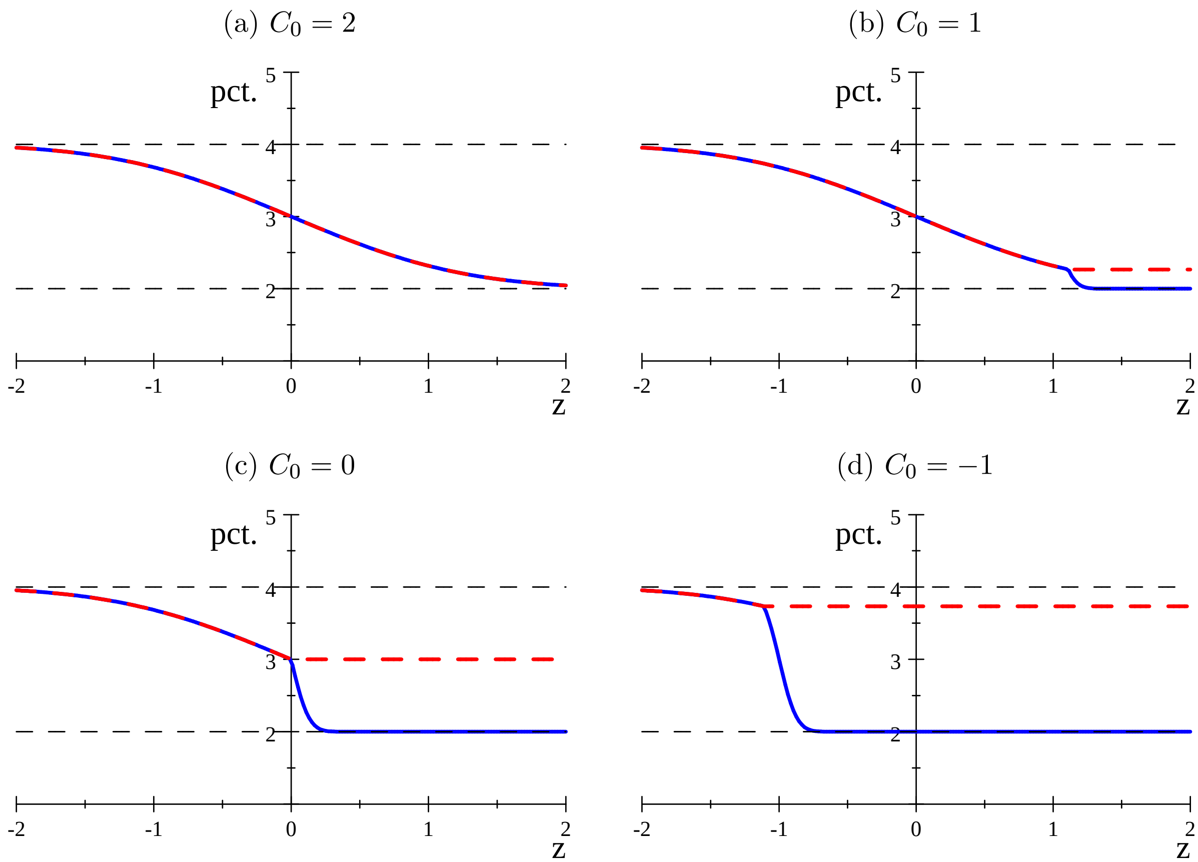
[15] Depending on trading and settlement arrangements, the central bank may or may not deal directly with banks in the open market operation considered in this section. What matters here is that banks hold fewer bonds on their balance sheets at the end of the day as a result of the operation.

the supply of reserves is equal to total required reserves. The equilibrium critical values for the payment shock ε^i in (16) then reduce to

$$\varepsilon_K^* = z, \quad \varepsilon_C^* = \frac{C_0}{0.9}, \quad \text{and} \quad \hat{\varepsilon}^* = \frac{z - C_0}{0.1},$$

where $C_0 \equiv B_0 + \theta_D D_0$ is the liquidity surplus of the banking system prior to the operation.

Figure 2 depicts equilibrium interest rates as functions of the change in reserves z. When banks have a large liquidity surplus, as in panel (a), the LCR is never a binding concern. In this case, the result in Corollary 2 applies for all values of z in the figure: the effects of open market operations are the same as in the standard model and there is no term premium. Note that the overnight interest rate is at the midpoint of the corridor when there are zero excess reserves in the banking system ($z = 0$); this point has been emphasized by Woodford (2001), Whitesell (2006) and others.



— overnight rate (r^*), - - term rate (r_T^*).

Figure 2: Effect of open market operations with banks using HQLA

When the liquidity surplus is smaller, as in panel (b), the figure shows how increasing the supply of reserves can introduce the effects described in Corollary 3. In particular, for sufficiently large values of z, the overnight rate is pushed lower – rapidly approaching the floor of the corridor – and a term premium emerges. The bottom two panels show that as the liquidity position of the banking system deteriorates further, these effects arise for smaller values of z and the size of the term premium increases. In panel (d), a substantial quantity of reserves must be removed to lift the overnight rate off the floor of the corridor, while the term rate remains close to the ceiling of the corridor regardless of the size of the operation.

To understand these patterns, recall that adding reserves through this type of operation does not change the total stock of HQLA held by the banking system, but shifts its composition to include more reserves. The likelihood that a bank will face an LCR deficiency is, therefore, unaffected by the operation, while the likelihood of it facing a reserve deficiency decreases. Looking back at Figure 1, higher values of z tend to move banks away from the situation depicted in panel (a) and toward the situation depicted in panel (b). Once panel (b) applies, additional increases in the supply of reserves sharply reduce the overnight rate as the reserve requirement becomes less likely to be a binding concern. Such increases have no effect on the term rate, however, since term borrowing helps a bank meet both types of requirement.

5.2 Operations with banks using non-HQLA

Now suppose the central bank conducts outright purchases of non-HQLA assets (loans or pools thereof) and that banks are again the sellers of these assets. In this case, the aggregate balance sheet and LCR of the banking system adjust as follows:

Assets		Liabilities	
Loans	$L_0 - z$	Deposits	D_0
Bonds	B_0		
Reserves	$R_0 + z$	Equity	E_0

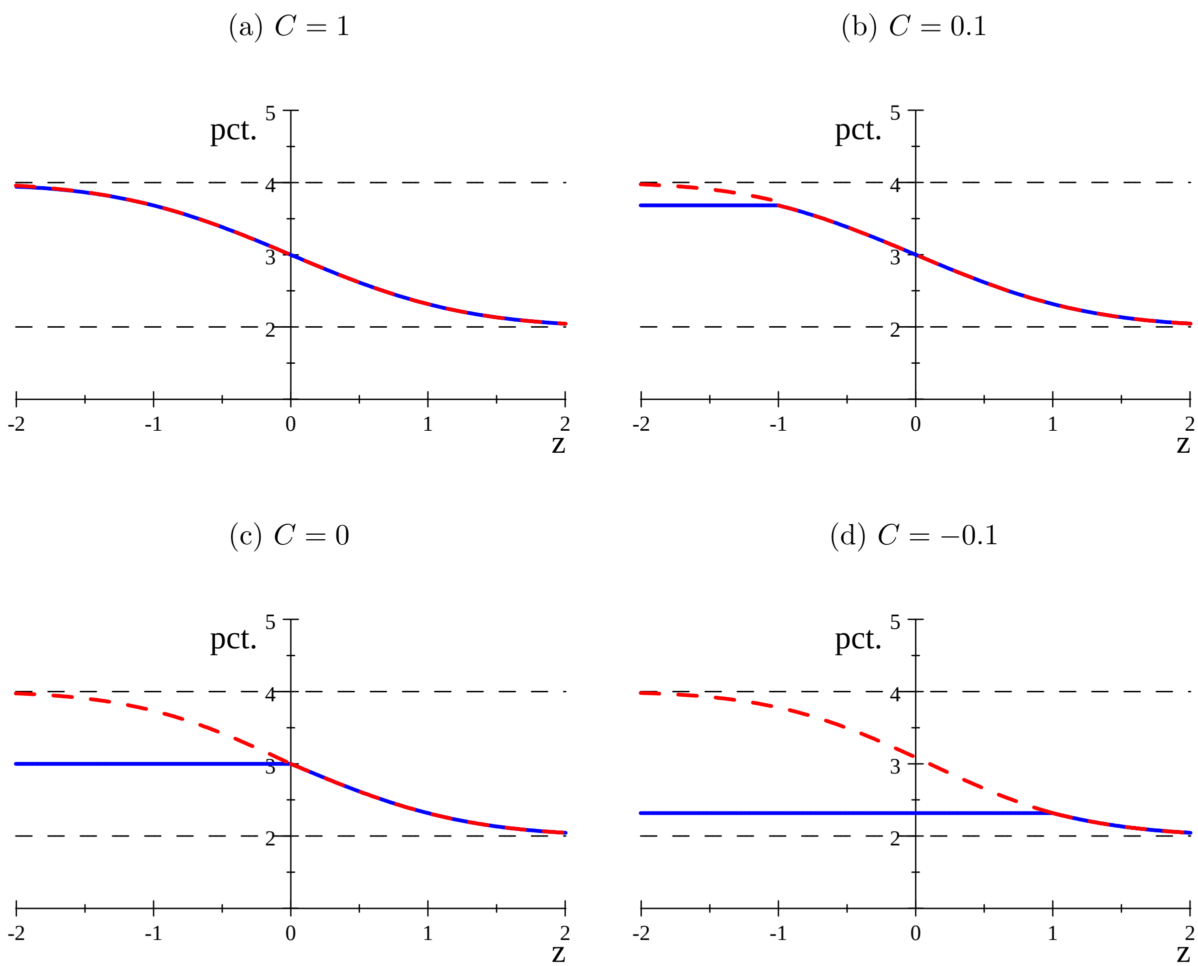
$$\Rightarrow \quad LCR_z = \frac{B_0 + R_0 + z}{\theta_D D_0} > LCR_0$$

While the size of this balance sheet is again unchanged, the operation now substitutes reserves for loans on bank balance sheets and thereby increases the pool of HQLA. There is again no effect on net cash outflows and, hence, the operation raises the LCR of the banking system. Adding reserves through purchases of non-HQLA thus makes the LCR less likely to bind and, as a result, the demand for interbank borrowing is more likely to be determined by the reserve requirement, which tends to lower the term premium. In the central bank instead *sells* loans using this type of operation, the LCR of the banking system will decrease and the value of term funding will tend to rise more than the value of overnight funding.

Figure 3 presents the relationship between the equilibrium interest rates and the size of the open market operation z for this case. In panel (a), banks have a large liquidity surplus and, as in the previous case, the behavior of the overnight rate is the same as in the standard model and the term premium is zero. In panel (b), the liquidity surplus is smaller and banks may experience an LCR deficiency in some states if a substantial quantity of reserves is removed by the central bank. The features described in Corollary 3 can be seen this panel: for sufficiently negative values of z, the overnight rate is lower than in the standard model and a term premium appears. Note that, once these feature appear, further decreases in the quantity of reserves have no effect on the overnight rate.

In moving to panel (c), the liquidity position of the banking system is decreased further. The two features discussed above – a lower overnight rate and a term premium – now appear for all negative values of z. In addition, the maximum value of the overnight rate is now lower; at the midpoint of the corridor. Panel (d) represents a case where the banking system has a liquidity deficit net of reserves. In this case, the overnight rate remains near the floor for all values of z; there is no size for the operation that will induce the overnight rate to trade at the midpoint of the corridor.

The differences between Figures 2 and 3 are striking. Whereas a term premium arises for sufficiently *large* values of z in Figure 2, it arises for sufficiently *small* values of z in Figure 3. In other words, the yield curve tends to steepen when the central bank adds reserves using operations with HQLA, but tends to flatten when reserves are added via operations with non-HQLA. Moreover, the responsiveness of the overnight rate to the size of the operation differs dramatically between the two cases. If HQLA are used in the operation, the overnight rate is very responsive to changes in reserves (i.e., the solid line in Figure 2 is very steep) when banks are concerned about the possibility of an LCR shortfall. If non-HQLA are used, in contrast, the overnight rate becomes completely unresponsive to the size of the operation (i.e., the solid line in Figure 3 is flat) in this situation. Finally, note that operations with HQLA can always be used to move the overnight rate to the midpoint of the corridor, regardless of the liquidity position of the banking system. Panel (d) of Figure 3 shows that this is not true when the operations use non-HQLA.



— overnight rate (r^*), - - term rate (r_T^*)

Figure 3: Effect of open market operations with banks using non-HQLA

These results illustrate how the effects of an open market operation can depend critically on its structure in the presence of an LCR requirement. In the next section, we investigate how the magnitude of these effects depends on one of the parameters of the regulation: the runoff-rate θ_X assigned to secured loans from the central bank.

6 Changing the runoff rate θ_X

The original LCR rules (BCBS, 2010) included a review clause that allowed for changes to be made to address concerns about possible unintended consequences. In January 2013, the Basel Committee issued a revised version of the rules text (BCBS, 2013). This revision included several changes to the LCR requirement, including an expansion in the range of assets eligible as HQLA and refinements to minimum standards for various inflow and outflow rates to better reflect actual experience in times of stress. Of particular interest in our context is the decision to reduce minimum the outflow rate on maturing secured funding transactions with central banks – our parameter θ_X – from 25% to 0%. How does changing this parameter affect the impact of the LCR on the process of monetary policy implementation?

The following proposition shows that decreasing θ_X tends to mitigate the effects of the LCR on equilibrium interest rates in our model. In particular, lowering θ_X will tend to increase the overnight rate and decrease the term rate, pulling both rates closer to the interest rate r^P that prevails when there is no LCR requirement.

Proposition 3 *The equilibrium overnight rate r^* is weakly decreasing in θ_X and the equilibrium term rate r_T^* is weakly increasing in θ_X.*

This result applies for all $\theta_X \geq 0$, including both the case of $\theta_X < \theta_D$ studied in Section 5 and the case of $\theta_X > \theta_D$ studied in Appendix B. A proof of this proposition is presented in Appendix C.

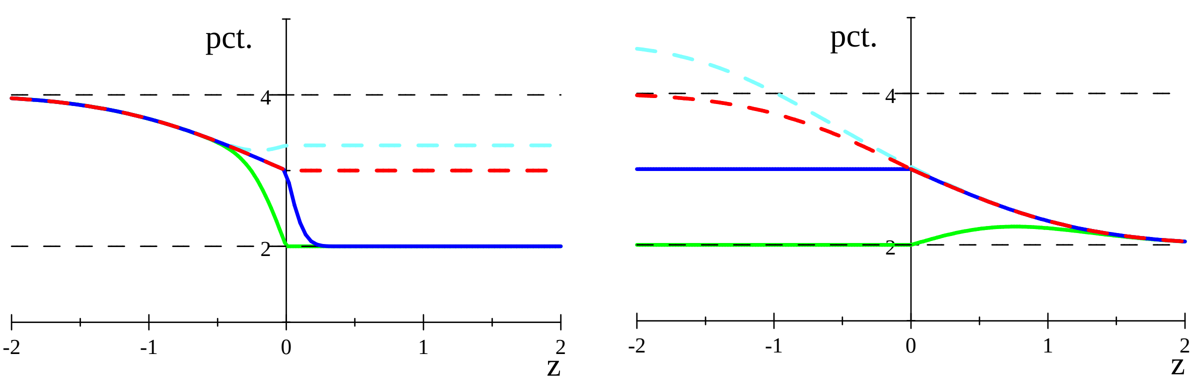
Figure 4 illustrates this result by plotting the equilibrium interest rates (r^*, r_T^*) associated with two different values of θ_X in each panel: $\theta_X = 0.25$ and $\theta_X = 0$. These runoff rates correspond to the minimum standards under the original and revised LCR rules, respectively. The two panels of the figure corresponds to the case where the central bank conducts outright purchases/sales of

HQLA (panel a) and of non-HQLA (panel b). The initial value of the liquidity surplus of the banking system (net of reserves) is set to $C_0 = 0$, which means that the interest rates associated with $\theta_X = 0$ are the same those in panel (c) of Figure 2 (for HQLA) and Figure 3 (for non-HQLA). The new curves in each panel are the equilibrium interest rates associated with $\theta_X = 0.25$.

For the case of operations with HQLA, when z is sufficiently small, the LCR is not a binding concern and the overnight rate is the same as in the standard model regardless of the value of θ_X. For sufficiently large values of z, the overnight rate is at the floor of the corridor for both values of θ_X. For intermediate values of z, however, we see that the overnight rate is lower when $\theta_X = 0.25$. The difference can be significant: when $z = 0$, the overnight rate is at the midpoint of the corridor with $\theta_X = 0$ but at the floor of the corridor with the higher value of θ_X. Similarly, the two dashed lines show that the term rate tends to be higher when $\theta_X = 0.25$. Overall, panel (a) of Figure 4 shows how moving from the higher value of the runoff rate to $\theta_X = 0$ pushes the overnight and term rates closer together, although a substantial term premium remains when z is positive.

(a) HQLA (b) Non-HQLA

$C_0 = 0$



$\theta_X = 25\%$: — r^*, - - - r_T^*,
$\theta_X = 0\%$: — r^*, - - - r_T^*.

$\theta_X = 25\%$: — r^*, - - - r_T^*,
$\theta_X = 0\%$: — r^*, - - - r_T^*.

Figure 4: Comparing $\theta_X = 0$ and $\theta_X > \theta_D$ for open market operations with banks

Panel (b) presents the corresponding figure for the case where the central bank conducts outright purchases/sales of non-HQLA. The same patterns arise here, and the differences between the two cases are even larger. With $\theta_X = 0$, the overnight rate lies at the midpoint of the corridor for all

$z < 0$. With $\theta_X = 0.25$, in contrast, the overnight rate lies on the floor of the corridor for all $z < 0$ and is lower than the interest rate from the standard model for any value of z. In addition, the term interest rate rises above the penalty rate r_X when $\theta_X = 0.25$, since a dollar of term borrowing in this case will save the bank from having to borrow $(1 - \theta_X)^{-1} > 1$ dollars from the central bank's lending facility in some states.

While the figure illustrates how lowering θ_X mitigates the effects of the LCR on equilibrium interest rates, note that these effects remain large even for the lowest possible value of the parameter, $\theta_X = 0$. Thus, when banks face the possibility of an LCR shortfall, the introduction of an LCR requirement can have a significant impact on the process of monetary policy implementation regardless of the value chosen for parameter θ_X.

7 Conclusions

The liquidity coverage ratio (LCR) introduced as part of the Basel III regulatory framework will change banks' demand for liquid assets and their behaviour in money markets. As many central banks implement monetary policy by targeting short-term interbank rates, it is important to understand the nature of these changes. What impact will the LCR requirement have on overnight and longer-term rates? How will these changes affect a central bank's ability to control interest rates using open market operations? We provide a first step in answering these questions.

Our analysis points to four central conclusions. First, the impact of the LCR will depend on the liquidity position of the banking system. If banks have a large surplus of liquid assets, introducing an LCR requirement has little or no effect. When banks face the possibility of an LCR shortfall, however, the requirement can change equilibrium interest rates substantially. Second, once the LCR is in place, the effect of an open market operation depends on how it is structured as well as its size. For example, outright purchases of high-quality liquid assets (HQLA) tend to create large changes in the overnight interest rate and a steepening of the yield curve, while purchases of non-HQLA may bring little-to-no change in the overnight rate and a flattening of the yield curve. In this environment, the central bank must consider how an operation affects all of the components of bank balance sheets that enter into the LCR calculation. Third, the LCR will likely introduce a regulatory-driven term premium, making the short end of the yield curve steeper. Finally, the treatment of central bank loans in the LCR calculation is an important determinant of the regulation's effects. By lowering the runoff rate assigned to these loans in the stress scenario, the final LCR rules described in BCBS (2013) mitigate — but do not eliminate — the regulation's effects on monetary policy implementation relative to the initial proposal.

There are several steps central banks can take to counter the impact of the regulation on the implementation of monetary policy. In some jurisdictions, it might be advantageous for the central bank to target a term interest rate rather than the overnight rate. The Swiss National Bank, for example, already implements its monetary policy in part by targeting the three-month Swiss franc Libor rate. Another option is for the central bank to offers loans of high-quality liquid assets to banks in a form other than reserves. Inspiration for such facilities can be taken from the Bank of England's Discount Window and the Federal Reserve's Term Securities Lending Facility, which have allowed participants to borrow, for a fee, gilts or treasuries against a range of less-liquid collateral. The LCR rules also permit central banks in jurisdictions where high-quality liquid assets may be in short supply to set up a contractually-committed liquidity facility that can be counted as part of a bank's stock of HQLA.

We have assumed here that the central bank's lending facility accepts illiquid assets as collateral and, hence, that banks can use this facility to increase their unencumbered holdings of HQLA and thereby meet their LCR requirement. If that is not the case, banks will likely shift their balance sheets to include more HQLA on an on-going basis, a move that could potentially affect other parts of the monetary policy transmission mechanism. At the June 2012 meeting of the Bank of England's Monetary Policy Committee (MPC), for example, concern was expressed "that regulatory liquidity requirements might be increasing the demand for reserves, attenuating the impact on the economy of the MPC's asset purchase programme and the associated increase in the supply of reserves."[16] Using an expanded model that accounts for how banks arrive at their initial balances sheets to understand how the new LCR requirement may impact these other aspects of monetary policy is an interesting avenue for future research.[17]

[16]See page 9 of www.bankofengland.co.uk/publications/Documents/records/fpc/pdf/2012/record1207.pdf

[17]Covas and Driscoll (2013) study how liquidity regulations can affect the composition of bank balance sheets in a

8 Appendices

A Proof of Proposition 1

To deal with the indicator function in the objective function (12), we examine the first-order conditions in the regions $\varepsilon_C^i \geq \varepsilon_K^i$ and $\varepsilon_C^i < \varepsilon_K^i$ separately. If $\varepsilon_C^i \geq \varepsilon_K^i$ holds, the indicator function is zero and we have $\max\left\{\varepsilon_k^i, \hat{\varepsilon}^i\right\} = \varepsilon_K^i$. The marginal benefits of overnight and term funding in this case are given by

$$\frac{\partial E[\pi^i]}{\partial \Delta^i} = -r + r_R + (r_X - r_R) \int_{\varepsilon_K^i}^{\infty} g\left(\varepsilon^i\right) d\varepsilon^i \tag{19}$$

and

$$\frac{\partial E[\pi^i]}{\partial \Delta_T^i} = -r_T + r_R + (r_X - r_R) \int_{\varepsilon_K^i}^{\infty} g\left(\varepsilon^i\right) d\varepsilon^i. \tag{20}$$

In the region where $\varepsilon_C^i < \varepsilon_K^i$ holds, the value of the indicator function is one, we have $\max\left\{\varepsilon_k^i, \hat{\varepsilon}^i\right\} = \hat{\varepsilon}^i$, and the marginal benefits are

$$\frac{\partial E[\pi^i]}{\partial \Delta^i} = -r + r_R + (r_X - r_R) \int_{\hat{\varepsilon}^i}^{\infty} g\left(\varepsilon^i\right) d\varepsilon^i \tag{21}$$

and

$$\frac{\partial E[\pi^i]}{\partial \Delta_T^i} = -r_T + r_R + (r_X - r_R) \left(\frac{1}{1-\theta_X} \int_{\varepsilon_C^i}^{\hat{\varepsilon}^i} g\left(\varepsilon^i\right) d\varepsilon^i + \int_{\hat{\varepsilon}^i}^{\infty} g\left(\varepsilon^i\right) d\varepsilon^i \right). \tag{22}$$

For the first part of the proposition, suppose that $r_T > r$ holds and consider the region where $\varepsilon_C^i \geq \varepsilon_K^i$. In this case, expressions (19) and (20) imply

$$\frac{\partial E[\pi^i]}{\partial \Delta^i} > \frac{\partial E[\pi^i]}{\partial \Delta_T^i},$$

meaning that the bank could increase its expected profit by borrowing one dollar less in the term market and one dollar more in the overnight market. It follows that the solution to the problem cannot lie in this region and, hence, must satisfy $\varepsilon_C^i < \varepsilon_K^i$. This solution is characterized by setting the derivatives (21) and (22) to zero, which yields

$$r = r_R + (r_X - r_R)\left(1 - G\left[\hat{\varepsilon}^i\right]\right)$$

general equilibrium setting, but do not address issues related to monetary policy and

$$r_T = r_R + (r_X - r_R)\left(1 - G\left[\hat{\varepsilon}^i\right] + \frac{G\left[\hat{\varepsilon}^i\right] - G\left[\varepsilon_C^i\right]}{1-\theta_X}\right),$$

which are equivalent to equations (13) and (14) from the statement of the proposition.

Now suppose that $r_T = r$ holds and consider the region where $\varepsilon_C^i < \varepsilon_K^i$ holds. In this case, the derivatives in (21) and (22) imply

$$\frac{\partial E[\pi^i]}{\partial \Delta^i} < \frac{\partial E[\pi^i]}{\partial \Delta_T^i},$$

meaning that the bank could increase its expected profit by borrowing one dollar more in the term market and one dollar less in the overnight market. It follows that the solution to the problem in this case cannot lie in this region and must instead satisfy $\varepsilon_C^i \geq \varepsilon_K^i$. The problem is solved in this case by any pair $\left(\Delta^i, \Delta_T^i\right)$ that equates both (19) and (20) to zero, which requires that ε_K^i satisfy

$$r = r_R + (r_X - r_R)\left(1 - G\left[\varepsilon_K^i\right]\right).$$

This is equation (15) from the statement of the proposition. ■

B The model with $\theta_X > \theta_D$

In this appendix, we study the case in which the LCR parameters are set so that the runoff rate on loans from the central bank, θ_X, is larger than the runoff rate on deposits, θ_D. While the expressions for the equilibrium interest rates are different from those derived in the main text, where we assumed $\theta_X < \theta_D$, we show that the same general patterns arise. The analysis in this appendix is used in Section 6 to provide results that apply for all $\theta_X \geq 0$.

When $\theta_X > \theta_D$ holds, the amount bank i must borrow from the central bank's lending facility to meet all of its regulatory requirements is still given by (7), but the pattern of borrowing depicted in Figure 1 in the main text changes to that in Figure 5. The principal difference is that the slope of the line associated with borrowing for LCR purposes is now steeper than the line associated with the reserve requirement. As a result, the LCR requirement now determines the amount borrowed for sufficiently large values of the payment shock in panel (a) and for all values of the payment shock in panel (b).

(a) $\varepsilon_K^i < \varepsilon_C^i$ (b) $\varepsilon_K^i > \varepsilon_C^i$

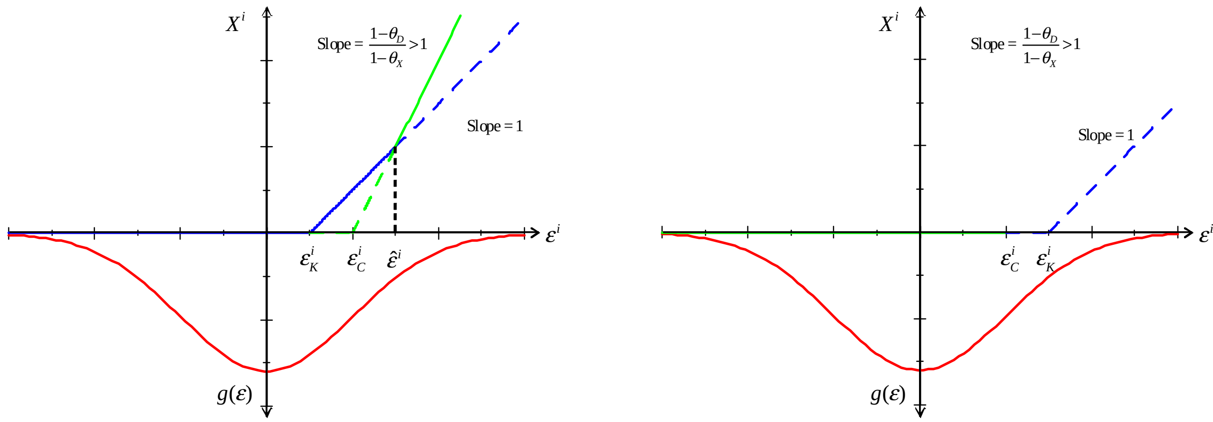


Figure 5: Bank i's borrowing from central bank lending facility (with $\theta_X > \theta_D$)

Bank i's maximization problem (12) changes to reflect these new patterns:

$$\max_{(\Delta^i, \Delta_T^i)} -r\Delta^i - r_T \Delta_T^i + r_R \left(R^i + \Delta^i + \Delta_T^i - K^i\right)$$
$$-(r_X - r_R) \left\{ \begin{array}{c} \mathbb{I}_{(\varepsilon_K^i < \varepsilon_C^i)} \int_{\varepsilon_K^i}^{\hat{\varepsilon}^i} \left(\varepsilon^i + K^i - R^i - \Delta^i - \Delta_T^i\right) g\left(\varepsilon^i\right) d\varepsilon^i \\ + \int_{\max\{\hat{\varepsilon}^i, \varepsilon_C^i\}}^{\infty} \frac{(1-\theta_D)\varepsilon^i - C^i - R^i - \Delta_T^i}{1-\theta_X} g\left(\varepsilon^i\right) d\varepsilon^i \end{array} \right\}.$$

The solution to this problem is characterized in the following proposition, the proof of which follows that of Proposition 1 closely and is omitted.

Proposition 4 *Suppose $\theta_X > \theta_D$. If $r > r_R$, the bank will choose $\left(\Delta^i, \Delta_T^i\right)$ so that the critical values $\left(\varepsilon_K^i, \varepsilon_C^i, \hat{\varepsilon}^i\right)$ defined in (8) – (10) satisfy*

$$r = r_R + (r_X - r_R)\left(G[\hat{\varepsilon}^i] - G[\varepsilon_K^i]\right) \quad \textit{and} \tag{23}$$

$$r_T = r + \frac{(r_X - r_R)}{1-\theta_X}\left(1 - G\left[\hat{\varepsilon}^i\right]\right). \tag{24}$$

If $r = r_R$, the bank will choose $\left(\Delta^i, \Delta_T^i\right)$ so that these values satisfy

$$\varepsilon_K^i \geq \varepsilon_C^i \quad \textit{and} \quad r_T = r + \frac{(r_X - r_R)}{1-\theta_X}\left(1 - G\left[\varepsilon_C^i\right]\right). \tag{25}$$

When the overnight interest rate is above r_R, equation (23) states that the bank will choose $\left(\Delta^i, \Delta_T^i\right)$ so that the expected marginal value of overnight funds equals the interest rate r in the overnight market. This entails choosing (Δ^i, Δ_T^i) so that $\varepsilon_K^i < \varepsilon_C^i < \hat{\varepsilon}^i$ holds, as depicted in panel (a) of Figure 5. Similarly, equation (24) states that the bank will equate its marginal value of term funds to the interest rate r_T in the term market. This marginal value is equal to the value of overnight funds r plus a term premium that is proportional to the probability that ε^i will be in the range where the bank's borrowing from the central bank is determined by its need to meet the LCR requirement.

When the overnight interest rate r is equal to r_R, the bank can increase its reserve holdings at no cost by borrowing funds in the overnight market and holding the funds in its reserve account. The first component of equation (25) states that, in this case, the bank will choose (Δ^i, Δ_T^i) so that $\varepsilon_K^i \geq \varepsilon_C^i$ holds, as in panel (b) of Figure 1, and the reserve requirement is never a binding concern. The second component says that the bank's marginal value of term funds again equals the value of overnight funds r plus a term premium, and that the bank will equate this marginal value to the interest rate r_T in the term market. Note that many pairs (Δ^i, Δ_T^i) will satisfy the two conditions in equation (25) and the bank will be indifferent between any of these actions.

Substituting the equilibrium critical values from (16) into the demand functions from Proposition 4 yields the equilibrium pricing relationships.

Proposition 5 *When $\theta_X > \theta_D$, the equilibrium interest rates are given by*

$$r^* = r_R + (r_X - r_R)\max\{G[\hat{\varepsilon}^*] - G[\varepsilon_K^*], 0\} \quad \textit{and} \tag{26}$$

$$r_T^* = r^* + \frac{(r_X - r_R)}{1-\theta_X}(1 - G[\max\{\hat{\varepsilon}^*, \varepsilon_C^*\}]). \tag{27}$$

This result provides the counterpart to Proposition 2 in the main text. As before, the equilibrium overnight rate is equal to the interest rate on reserves r_R plus a spread that reflects the marginal value of overnight funds in avoiding a deficiency in a bank's reserve requirement. The equilibrium term rate equals the overnight rate plus a term premium that reflects the marginal value of term funding in avoiding a deficiency in the LCR requirement. The expressions differ from those in Proposition 2 because of the different pattern of borrowing X^i needed to satisfy the bank's two requirements, as depicted in Figures 1 and 5. Proposition 5 is used in Section 6 of the text (especially in establishing Proposition 3) to provide results that apply for all $\theta_X \geq 0$.

C Proof of Proposition 3

First note that the equilibrium critical values ε_K^* and ε_C^* in (16) do not depend on θ_X, whereas $\hat{\varepsilon}^*$ does depend on θ_X, with

$$\frac{\partial \hat{\varepsilon}^*}{\partial \theta_X} = -\frac{C + (1-\theta_D) K + \theta_D R}{(\theta_X - \theta_D)^2} \tag{28}$$

for any $\theta_X \neq \theta_D$. The proof is divided into three cases.

Case (i) : The region where $\theta_X < \theta_D$

In this case, Proposition 2 shows that r^* is a decreasing function of

$$\max\{\hat{\varepsilon}^*, \varepsilon_K^*\}. \tag{29}$$

If $\hat{\varepsilon}^* \leq \varepsilon_K^*$, then (29) is independent of θ_X. For the reverse case, one can use (16) and (28) to show that the following inequalities are equivalent:

$$\hat{\varepsilon}^* > \varepsilon_K^* > \varepsilon_C^* \quad \Leftrightarrow \quad C + (1-\theta_D) K + \theta_D R < 0 \quad \Leftrightarrow \quad \frac{\partial \hat{\varepsilon}^*}{\partial \theta_X} > 0. \tag{30}$$

This expression shows that if $\hat{\varepsilon}^* > \varepsilon_K^*$, then $\hat{\varepsilon}^*$ – and hence (29) – is strictly increasing in θ_X. The expression in (29) is thus a weakly increasing function of θ_X and, therefore, r^* is a weakly decreasing function of θ_X in the region $\theta_X < \theta_D$.

Proposition 2 also shows that r_T^* is a strictly increasing function of

$$\max\{G[\hat{\varepsilon}^*] - G[\varepsilon_C^*], 0\}. \tag{31}$$

Again using (30), it follows that (31) is a weakly increasing function of θ_X. Combined with the $(1-\theta_X)$ term in the denominator of (18), this implies that r_T^* is a weakly decreasing function of θ_X in the region $\theta_X < \theta_D$.

Case (ii) : The region where $\theta_X > \theta_D$

We now establish that these same results hold in the region $\theta_X > \theta_D$. In this case, Proposition 5 shows that r^* is a strictly decreasing function of

$$\max\{G[\hat{\varepsilon}^*] - G[\varepsilon_K^*], 0\}. \tag{32}$$

Equations (16) and (28) imply that, for this case, the following inequalities are equivalent:

$$\hat{\varepsilon}^* > \varepsilon_C^* > \varepsilon_K^* \quad \Leftrightarrow \quad C + (1-\theta_D) K + \theta_D R > 0 \quad \Leftrightarrow \quad \frac{\partial \hat{\varepsilon}^*}{\partial \theta_X} < 0. \tag{33}$$

In other words, we have either $\hat{\varepsilon}^* \leq \varepsilon_K^*$, in which case (32) is zero and independent of θ_X, or $\hat{\varepsilon}^* > \varepsilon_K^*$, in which chase $\hat{\varepsilon}^*$ and (32) are strictly decreasing functions of θ_X. The expression in (32) is thus a weakly decreasing function of θ_X, which implies that r^* is a weakly decreasing function of θ_X in the region $\theta_X > \theta_D$ as well.

Similarly, Proposition 5 shows that r_T^* is a decreasing function of

$$\max\left\{\hat{\varepsilon}^*, \varepsilon_C^*\right\}. \tag{34}$$

Again using (33), it follows that (34) is a weakly decreasing function of θ_X. Combined with the $(1-\theta_X)$ term in the denominator of (27), this implies that r_T^* is a weakly decreasing function of θ_X in the region $\theta_X > \theta_D$.

Case (iii) : Comparing across regions

What remains is to connect the two cases above by establishing that r^* is always lower in case (i) than in case (ii) and that the reverse holds for r_T^*. For example, while there may be a discontinuity in the function $r^*(\theta_X)$ at $\theta_X = \theta_D$, the discontinuity would always represent a jump down in the overnight rate and not a jump up.

Let $(\tilde{r}^*, \tilde{r}_T^*, \tilde{\varepsilon}^*)$ denote the equilibrium values associated with some $\tilde{\theta}_X > \theta_D$. Then using Propositions 2 and 5, we can write the difference between r^* and $\tilde{r}^*$ as

$$r^* - \tilde{r}^* = (r_X - r_R)\left(1 - G\left[\max\left\{\hat{\varepsilon}^*, \varepsilon_K^*\right\}\right] - \max\left\{G\left[\tilde{\varepsilon}^*\right] - G\left[\varepsilon_K^*\right], 0\right\}\right). \tag{35}$$

Using (16), one can show that the ordering of the equilibrium critical values must be either

$$\hat{\varepsilon}^* > \varepsilon_K^* > \varepsilon_C^* > \tilde{\varepsilon}^* \tag{36}$$

or

$$\hat{\varepsilon}^* \leq \varepsilon_C^* \leq \varepsilon_K^* \leq \tilde{\varepsilon}^*, \tag{37}$$

depending on parameter values. In case (36), the difference in (35) evaluates to

$$(r_X - r_R)(1 - G[\hat{\varepsilon}^*]) \geq 0.$$

In case (37), the difference evaluates to

$$(r_X - r_R)(1 - G[\tilde{\varepsilon}^*]) \geq 0.$$

In both cases, therefore, we have $r^* \geq \tilde{r}^*$.

Turning to the term rate, Propositions 2 and 5 allow us to write

$$\begin{aligned} r_T^* - \tilde{r}_T^* &= (r_X - r_R)(1 - G[\max\{\hat{\varepsilon}^*, \varepsilon_K^*\}] - \max\{G[\tilde{\varepsilon}^*] - G[\varepsilon_K^*], 0\}) \\ &\quad + \frac{r_X - r_R}{1 - \theta_X}(\max\{G[\hat{\varepsilon}^*] - G[\varepsilon_C^*], 0\} - 1 + G[\max\{\tilde{\varepsilon}^*, \varepsilon_C^*\}]). \end{aligned}$$

In case (36), this difference evaluates to

$$\begin{aligned} r_T^* - \tilde{r}_T^* &= (r_X - r_R)(1 - G[\hat{\varepsilon}^*]) + \frac{r_X - r_R}{1 - \theta_X}(G[\hat{\varepsilon}^*] - G[\varepsilon_C^*] - 1 + G[\varepsilon_C^*]) \\ &= (r_X - r_R)(1 - G[\hat{\varepsilon}^*]) - \frac{r_X - r_R}{1 - \theta_X}(1 - G[\hat{\varepsilon}^*]) \\ &= -(r_X - r_R)\frac{\theta_X}{1 - \theta_X}(1 - G[\hat{\varepsilon}^*]) \leq 0. \end{aligned}$$

In case (37), the difference evaluates to

$$\begin{aligned} r_T^* - \tilde{r}_T^* &= (r_X - r_R)(1 - G[\varepsilon_K^*] - G[\tilde{\varepsilon}^*] + G[\varepsilon_K^*]) - \frac{r_X - r_R}{1 - \theta_X}(1 - G[\tilde{\varepsilon}^*]) \\ &= (r_X - r_R)(1 - G[\tilde{\varepsilon}^*]) - \frac{r_X - r_R}{1 - \theta_X}(1 - G[\tilde{\varepsilon}^*]) \\ &= -(r_X - r_R)\frac{\theta_X}{1 - \theta_X}(1 - G[\tilde{\varepsilon}^*]) \leq 0. \end{aligned}$$

In both cases, therefore, we have $r_T^* \leq \tilde{r}_T^*$. We have thus established that r^* is weakly larger and r_T^* weakly smaller for any $\theta_X < \theta_D$ than for any $\theta_X > \theta_D$, which completes the proof. ∎

D Other types of open market operations

In this appendix, we study the effects of two types of open market operations not considered in Section 5: (*i*) reverse operations and (*ii*) operations with non-bank counterparties, that is, with institutions that are not active in interbank markets and not subject to reserve or LCR requirements.

D.1 Reverse operations

In a reverse operation, the exchange of reserves for collateral between the central bank and its counterparty is reversed at a pre-specified future date. As with the outright operations studied in Section 5, the effects of a reverse operation depend crucially on the type of assets used.

D.1.1 Reverse operations with banks using HQLA

If the central bank adds reserves via reverse operations using HQLA as collateral, the LCR of the banking system will decrease to the extent the central bank applies a haircut. This occurs because the stock of high-quality liquid assets used in the LCR calculation only includes assets that are unencumbered and, when a haircut is applied, the quantity of assets encumbered is greater than the quantity of reserves created, as shown below:

Assets		Liabilities	
Loans	L	Deposits	D
Bonds	B	Central bank repo	z
- encumbered	$z/(1-\alpha)$		
Reserves	$R+z$	Equity	E

$$\Rightarrow \quad LCR_z = \frac{B + R - \frac{\alpha}{1-\alpha} z}{\theta_D D} < LCR_0,$$

where α denotes the haircut on bonds set by the central bank. In other words, one unit of reserves is exchanged for $\frac{1}{1-\alpha}$ units of bonds, which shrinks the stock of HQLA even though the total amount of liquid assets held by the banking system increases. In practice, however, the haircuts applied to high-quality liquid assets by central banks are typically small and, hence, the change in the LCR caused by such operations is minor. In this case, the effects of an open market operation are very similar to the outright operations studied in Section 5.1 and illustrated in Figure 2.

D.1.2 Reverse operations with banks using non-HQLA

If the central adds reserves via reverse operations using non-HQLA as collateral, the balance sheet of the banking system adjusts as follows:

Assets		Liabilities	
Loans	L	Deposits	D
-encumbered	$z/(1-\beta)$	Central bank repo	z
Bonds	B		
Reserves	$R{+}z$	Equity	E

$$\Rightarrow \quad LCR_z{=}\frac{B+R+z}{\theta_D D} > LCR_0,$$

where β is the haircut set by the central bank for illiquid assets. Because the assets being encumbered in this case are loans, the effect of the operation on the LCR of the banking system and on equilibrium interest rates is the same as with an outright purchase of non-HQLA. The results of this operation are thus identical to those studied in Section 5.2 and illustrated in Figure 3.

D.2 Operations with non-banks

Finally, we consider the case where the central bank conducts operations (either outright or reverse) with non-banks. The adjustments to the aggregate balance sheet and LCR of the banking system in this case are as follows:

Assets		Liabilities	
Loans	L	Deposits	$D+z$
Bonds	B		
Reserves	$R+z$	Equity	E

$$\Rightarrow \quad LCR_z{=}\frac{B-R{+}z}{\theta_D(D{+}z)} > LCR_0.$$

The funds due to the non-bank sector are credited to the banking system as reserves and the non-bank sector receives an equal claim on banks in form of deposits. Consequently, the balance sheet of the banking system expands. The stock of high-quality liquid assets grows by the amount of the reserves. This increase is partly offset in the LCR calculation by a rise in the net cash outflows due to the additional deposits. However, as the runoff rate θ_D on the newly-created deposits is well below 100%, the LCR rises. Notice that, in this case, the type of assets involved does not matter for determining the change in the LCR.

Figure 6 illustrates the effects of open market operations with non-banks. As in the case of operations with banks using non-HQLA (Figure 3), a term premium tends to arise when z is small. The size of the term premium is no longer monotone in z, however. As shown in panels (b) and (c), the term premium may be largest for values of z slightly below zero and then shrink as reserves are lowered beyond that point. Also as in Figure 3, the central bank may not be able to steer the overnight rate towards the midpoint of the corridor.

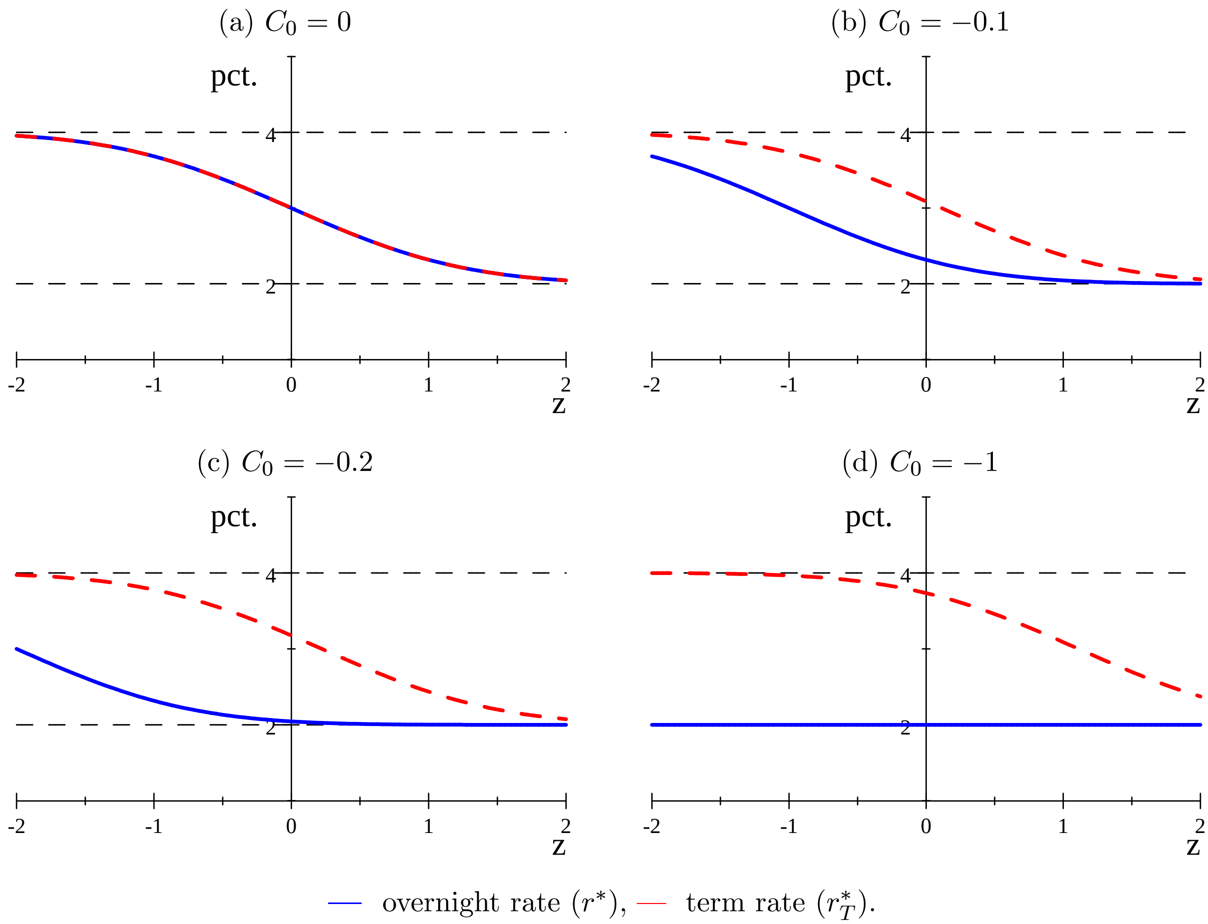


Figure 6: Open market operations with banks using non-HQLA

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