Liquidity regulation and the implementation of monetary policy*

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Abstract

We study the impact of the Basel III liquidity coverage ratio (LCR) on interbank interest rates in an otherwise-standard model of monetary policy implementation. We show that when banks face the possibility of an LCR shortfall, the overnight interest rate tends to *decrease*, while a regulatory *premium* arises in longer-term rates. In addition, the LCR requirement can substantially alter the effect of a central banks' open market operations on equilibrium interest rates.

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1 Introduction

In response to the recent global financial crisis, the Basel Committee on Banking Supervision (BCBS) announced a revised international regulatory framework known as Basel III. This framework introduced – for the first time – standards for managing banks' liquidity risk, comprised of the *liquidity coverage ratio* (LCR) and the *net stable funding ratio* (NSFR).[1] These standards aim to promote financial stability by influencing how banks manage the maturity mismatch between their assets and liabilities and "to prevent central banks becoming the 'lender of first resort'" in a liquidity crisis (BCBS, 2013a). In the process of doing so, the new regulations will likely affect market interest rates and, therefore, have implications for monetary policy. Because central bank reserves are liquid assets, for example, the new requirements will alter trading incentives in interbank markets, where banks borrow/lend these reserves from one another. In addition, a central bank's monetary policy operations may change banks' compliance with the regulations, at least at the margin, and thus further alter their trading incentives. These linkages raise the possibility that the new regulations could interfere with a central bank's ability to implement monetary policy by steering market interest rates to a desired target level.

We extend a standard model of interbank borrowing/lending to study how the introduction of an LCR requirement affects the process of implementing monetary policy. While there has been some policy-oriented discussion of this topic,[2] ours is the first model to analyze these issues systematically. We use this model to address two fundamental questions: how does the introduction of an LCR requirement affect interbank interest rates, and how does it change the impact of a central bank's monetary policy operations?

Our model makes clear predictions for the LCR's impact on equilibrium interest rates. A bank facing the possibility of an LCR shortfall has a stronger incentive to seek funding that receives favorable regulatory treatment, such as term loans of more than 30 days, and is more likely to borrow from the central bank's standing facilities. Both of these actions add to the bank's reserve holdings and thus lower its need to seek funds in the overnight market to ensure its reserve requirement is met. This lower demand drives *down* the overnight interest rate in equilibrium. In term interest rates, in contrast, an *LCR premium* arises that reflects each type of loan's value in satisfying the new regulation.

[1] The LCR and NSFR differ in part by focusing on distinct time horizons (30 days and one year, respectively). The LCR requirement is being phased in gradually, beginning at 60% coverage in January 2015 and rising 10 percentage points each year to reach 100% in January 2019. The NSFR is scheduled to take effect in January 2018.

[2] See, for example, Bindseil and Lamoot (2011), Schmitz (2013), ECB (2013), and Aaron et al. (2015).

Our model suggests that precisely controlling interest rates using open market operations (OMOs) may be more difficult when an LCR requirement is in place. When there is no LCR requirement, the overnight interest rate is determined by the total quantity of reserves supplied by the central bank. In such an environment, only the size of an OMO matters for interest rates; the details of the operation (assets used, counterparties, etc.) are irrelevant. Once an LCR requirement is introduced, this result no longer holds. The structure of an OMO determines its effects on bank balance sheets and, hence, on the likelihood of a bank facing an LCR shortfall. This likelihood, in turn, affects banks' incentives to trade in interbank markets. For some types of operations the overnight interest rate becomes more responsive to changes in the supply of reserves than in the standard model, while for others it becomes unresponsive. Similarly, the equilibrium LCR premium increases when the central bank adds reserves with some types of operations, but decreases for others. The magnitude of these effects depends on a variety of factors, some of which may be unknown to the central bank when the operation takes place.

The paper is organized as follows: We begin with a brief overview of the LCR regulation in the next section before presenting our model in Section 3 and its solution in Section 4. We then study how the LCR requirement affects equilibrium interest rates in Section 5 and how it impacts a central bank's ability to control interest rates using OMOs in Section 6. We offer brief concluding remarks in Section 7.

2 The liquidity coverage ratio (LCR)

The LCR 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 be at least one,

$$LCR = \frac{\textit{Stock of unencumbered HQLA}}{\textit{Net cash outflows over the next 30 calendar days}} \geq 1. \tag{1}$$

A bank's stock of unencumbered HQLA includes it holdings of cash, central bank reserves and certain marketable securities backed by sovereigns and central banks (called Level 1 assets) plus certain other assets (called Level 2) subject to limits and appropriate haircuts. The denominator of the LCR 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. From these outflows, banks are permitted to subtract expected inflows for 30 calendar days into the future, subject to certain limits.

The LCR rules require that the ratio be calculated at least monthly, with the operational capacity to do so daily in stressed situations (BCBS, 2013b). However, national supervisors have the option to require daily calculation of the LCR at all times, and some – including the U.S. – have chosen to do so (see Federal Register, 2014). Either way, banks are expected to meet the requirement in (1) on a continuous basis in normal times. During a period of stress, 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, in which banks are expected to fully meet the requirement.

3 The model

Our analysis is based on a model of competitive interbank markets in the tradition that began with Poole (1968).[3] There is a single time period that is divided into three stages. The economy consists of a continuum of banks, indexed by $i \in [0, 1]$, a central bank, and a set of investors representing non-bank financial firms and households. Two assets are in positive net supply: loans and bonds. In this section we describe the timing of events and banks' payoffs.

3.1 Balance sheets and timeline

Each agent begins the period with a balance sheet of the form in Figure 1. Banks have accepted deposits and hold loans, bonds and reserves as assets. The central bank also holds loans and/or bonds, which it purchased by issuing reserves in the past. Non-bank investors hold loans and bonds in addition to deposits at banks. Agents' equity positions play no role in our analysis and will be constant over the period. Total reserves held by banks equal the quantity of reserves issued by the central bank and total deposits issued by banks equal the deposits held by non-bank investors.

[3] Papers in this tradition 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), Vari (2016), and Boutros and Witmer (2017). Ennis and Keister (2008) provides a non-technical introduction.

Similarly, the quantities of loans and bonds held by each group sum to the fixed supply of each asset. We take the initial values of the variables in these balance sheets as given, reflecting activity that takes place before our model begins.

Bank i

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

Central Bank

Assets		Liabilities	
Loans	L^{CB}	Reserves	R^{CB}
Bonds	B^{CB}	Equity	Y^{CB}

Non-banks

Assets		Liabilities	
Loans	L^N		
Bonds	B^N		
Deposits	D^N	Equity	Y^N

Figure 1: Balance sheets after open market operation

In the first stage, the central bank buys or sells assets. This operation changes the balance sheets of banks and of non-bank investors; we study this process in detail in Section 6. For now, we take the values in Figure 1 as representing the situation *after* the central bank's operation has occurred and ask how equilibrium interest rates depend on the properties of these balance sheets.

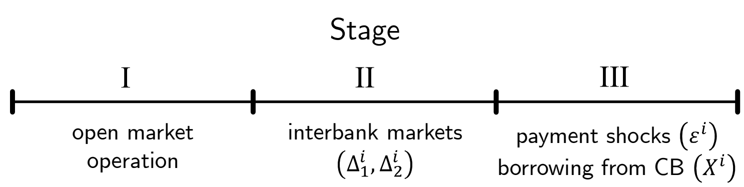

Figure 2: Timeline

In the second stage, banks can borrow and lend in interbank markets as indicated in Figure 2. Two distinct types of contracts are traded. We use $t = 1, 2$ to index these types, which we interpret as overnight and term loans, respectively. The only difference between the contracts in our model, however, is how they enter banks' LCR calculation, which we describe below. Let Δ_1^i and Δ_2^i denote the amounts bank i borrows in each interbank market; negative values correspond to lending. This activity introduces a new category in bank i's balance sheet, shown as "net interbank borrowing" in Figure 3. Because borrowing can be either positive or negative, the Δ_t^i terms can either be liabilities (as shown in the figure) or assets (i.e., claims on other banks). In either case, the new entries balance with the change in the bank's reserve holdings from interbank trading.

Bank i

Assets		Liabilities	
Loans	L^i	Deposits	$D^i - \varepsilon^i$
Bonds	B^i	Net interbank borrowing	$\Delta_1^i + \Delta_2^i$
Reserves	$R^i + \Delta_1^i + \Delta_2^i - \varepsilon^i + X^i$	Borrowing from CB	X^i
		Equity	Y^i

Figure 3: End-of-period balance sheet of bank i

In the third stage, after the interbank market has closed, an amount ε^i of bank i's customer deposits is sent as a payment to another bank. The value of ε^i for each bank is drawn from a common distribution G with a continuous density function, zero mean, and bounded support. This payment shock represents the unanticipated component of a bank's late-day customer payment activity; if ε^i is negative, the bank experiences an unexpected inflow of funds. The assumption that the interbank market closes before these 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.[4] Depending on ε^i, a bank may need to borrow from the central bank at the end of the period to meet its regulatory requirements. Let $X^i \geq 0$ denote the amount bank i borrows, which increases its reserves and adds a new liability, as shown in Figure 3. In the next few subsections, we discuss the how X^i is determined by a bank's regulatory requirements.

3.2 The reserve requirement

Each bank faces a reserve requirement of the form

$$R^i + \sum_{t=1,2} \Delta_t^i - \varepsilon^i + X^i \geq K^i. \tag{2}$$

[4] Ennis and Weinberg (2012), Afonso and Lagos (2015), and Bech and Monnet (2016) 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 within a trading day. See Bech and Klee (2011) and Armenter and Lester (2017) for alternative models of monetary policy implementation designed to study features of environments with very high levels of bank reserves.

The left-hand side of this expression is the bank's reserve holdings at the end of the period, taking into account funds borrowed/lent in interbank markets, the payment shock, and borrowing from the central bank. The right-hand side is the requirement for the period.[5] If the bank would violate this requirement after the realization of the payment shock, it must borrow funds from the central bank to ensure that (2) holds. Let

$$E_R^i \equiv R^i + \sum_{t=1,2} \Delta_t^i - K^i \tag{3}$$

denote bank i's *excess reserves* after interbank trading. The minimum amount bank i must borrow to fulfill the reserve requirement in (2) is then given by

$$X_R^i \equiv \max\left\{\varepsilon^i - E_R^i, 0\right\}. \tag{4}$$

3.3 The LCR requirement

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

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

Recall from (1) that the numerator of the ratio is the total value of the bank's unencumbered HQLA, which here simply equals its end-of-period holdings of bonds plus reserves.[6] The denominator measures the 30-day net cash outflow under the stress scenario. Deposits are assigned a runoff rate of $\theta_D > 0$, while interbank loans of type t are assigned runoff rate θ_t. We assume $\theta_1 = 1$ and $\theta_2 \in [0, 1)$, meaning that overnight (type-1) loans are assigned a 100% runoff rate while term (type-2) loans are assigned a lower rate. We assume the runoff rate for loans from the central bank, denoted θ_X, is lower than the runoff rate on deposits.[7]

Let X_{LCR}^i denote the minimum amount bank i must borrow from the central bank to fulfill the

[5] The reserve requirement can be thought of as depending on a bank's past deposit liabilities, but is a fixed number when the period begins. The model can represent a setup with no reserve requirement by setting K^i to zero for all i. 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.

[6] For simplicity, we assume that reserves held to meet reserve requirements are included in the calculation of HQLA. The LCR rules allow this approach under some conditions (see BCBS, 2013b). It is straightforward to modify the model to exclude these balances; doing so decreases the stock of HQLA in the economy and thereby amplifies the effects we describe below. See Bech and Keister (2013) for a richer extension of the model in which banks' committed credit lines from the central bank are included in the calculation of a bank's HQLA.

[7] The LCR rules allow θ_X to be as low as zero but, as these rules are a minimum standard, local authorities can set a higher value. We show in the supplemental appendix that the effects we highlight in the paper are amplified when θ_X is instead set higher than θ_D.

LCR requirement in (5), which is given by

$$X^i_{LCR} \equiv \max\left\{\frac{1-\theta_D}{1-\theta_X}\left(\varepsilon^i - E^i_{LCR}\right), 0\right\} \tag{6}$$

where

$$E^i_{LCR} \equiv \frac{B^i + R^i - \theta_D D^i + \sum_t (1-\theta_t)\,\Delta^i_t}{1-\theta_D}. \tag{7}$$

We refer to E^i_{LCR} as bank i's *excess LCR liquidity*. This variable measures the maximum deposit outflow the bank could experience and still satisfy its LCR requirement. If E^i_{LCR} is negative, bank i will need a sufficiently large payment inflow to avoid an LCR shortfall. Note that E^i_{LCR} measures a bank's cushion/shortfall relative to its LCR requirement in precisely the same way that E^i_R defined in (3) measures its cushion/shortfall relative to its reserve requirement.

3.4 Borrowing from the central bank

The minimum amount bank i must borrow from the central bank to meet both its reserve and LCR requirements is

$$X^i = \max\left\{X^i_R, X^i_{LCR}\right\}. \tag{8}$$

Figure 4 depicts X^i as a function of the realized payment shock ε^i. The steeper (blue) line in each panel represents (4), borrowing needed to satisfy the reserve requirement. This value is positive when the payment outflow ε^i is larger than the bank's excess reserves E^i_R. The flatter (green) line represents (6), borrowing needed to satisfy the LCR requirement, which is positive when ε^i is larger than the bank's excess LCR liquidity E^i_{LCR}. The bank's borrowing X^i is the upper envelope of these two lines.

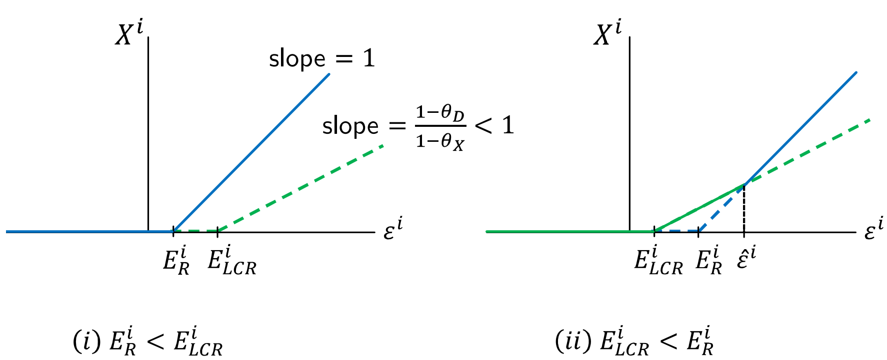

Figure 4: Bank i's borrowing from the central bank

As the figure shows, two distinct cases arise. In panel (i), the bank's excess LCR liquidity is larger than its excess reserves. In this case, X^i is always determined by the bank's need to meet its reserve requirement. In panel (ii) of the figure, the bank's excess LCR liquidity is smaller than its excess reserves and X^i can be determined by either of the two requirements, depending on the realized value of ε^i. In particular, X^i is determined by the LCR requirement for values of ε^i in the interval $\left(E^i_{LCR}, \hat{\varepsilon}^i\right)$, where

$$\hat{\varepsilon}^i \equiv \frac{(1-\theta_X)\, E^i_R - (1-\theta_D)\, E^i_{LCR}}{\theta_D - \theta_X}. \tag{9}$$

3.5 Discussion

Our model represents the minimal departure from the standard framework that allows us to address the effect of an LCR requirement on equilibrium interest rates. By studying a single-period setting, we are abstracting from the factors that usually generate spreads between overnight and term rates, such as expected future changes in interest rates and compensation for liquidity/credit risk. This approach permits us to focus cleanly on the effects of liquidity regulation. Because the only difference between the two loan contracts in our model is their treatment in the LCR calculation, any spread that arises in equilibrium is clearly due to the new regulation.

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.

4.1 Profits

A 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_t on its interbank borrowing (or lending) of type t. The bank earns r_K on reserves held to meet its reserve requirement and r_R on any excess reserves. In addition, it faces a penalty rate $r_X > r_R$ for funds borrowed from the central bank's lending facility.[8] Adding these terms together yields bank i's realized profit for the period,

$$\pi^i\left(\varepsilon^i\right) = r_L L^i + r_B B^i - r_D\left(D^i - \varepsilon^i\right) - \textstyle\sum_t r_t \Delta^i_t + r_K K^i + r_R\left(E^i_R + X^i - \varepsilon^i\right) - r_X X^i. \tag{10}$$

[8] This penalty rate should be interpreted as including the value of any stigma associated with borrowing from the central bank; see Ennis and Weinberg (2012) and Armantier et al. (2015).

Let Ψ^i denote the sum of all terms in (10) that are all fixed when the interbank market opens. Using (8) and $\mathbb{E}\left[\varepsilon^i\right]=0$, we can then write the expected value of bank i's profit before its payment shock is realized as

$$\begin{aligned} \mathbb{E}\left[\pi^i\right] &= \Psi^i - \textstyle\sum_t r_t \Delta_t^i + r_R E_R^i \\ &\quad -(r_X - r_R)\mathbb{E}\left[\max\left\{\varepsilon^i - E_R^i, \frac{1-\theta_D}{1-\theta_X}\left(\varepsilon^i - E_{LCR}^i\right), 0\right\}\right]. \end{aligned} \tag{11}$$

4.2 The demand for interbank loans

Bank i will choose its interbank borrowing activity $\left\{\Delta_t^i\right\}$ to maximize its expected profit (11). Dropping the constant term, we can write the objective function as

$$-\textstyle\sum_t r_t \Delta_t^i + r_R E_R^i - (r_X - r_R)\left\{\begin{array}{c} \mathbb{I}_{\left(E_{LCR}^i < E_R^i\right)} \int_{E_{LCR}^i}^{\hat{\varepsilon}^i} \frac{1-\theta_D}{1-\theta_X}\left(\varepsilon^i - E_{LCR}^i\right) dG\left(\varepsilon^i\right) \\ + \int_{\max\left\{E_R^i, \hat{\varepsilon}^i\right\}}^{\infty} \left(\varepsilon^i - E_R^i\right) dG\left(\varepsilon^i\right) \end{array}\right\}, \tag{12}$$

where the indicator function $\mathbb{I}$ takes the value one if the expression in parentheses is true and zero otherwise, E_R^i and E_{LCR}^i are functions of the choice variables $\left\{\Delta_t^i\right\}$ as shown in (3) and (7), and $\hat{\varepsilon}^i$ is as defined in (9). Absence of arbitrage requires $r_2 \geq r_1 \geq r_R$; otherwise unbounded profits would be possible and the problem would have no solution. Assuming this condition holds, the solution is characterized in the following proposition, a proof of which is provided in the supplemental appendix.

Proposition 1 *Bank i will choose $\left\{\Delta_t^i\right\}$ so that $\left(E_R^i, E_{LCR}^i\right)$ satisfy*

$$r_t = r_R + (r_X - r_R)\left(\begin{array}{c} 1 - G\left[\max\left\{E_R^i, \hat{\varepsilon}^i\right\}\right] \\ + \frac{1-\theta_t}{1-\theta_X}\max\left\{G\left[\hat{\varepsilon}^i\right] - G\left[E_{LCR}^i\right], 0\right\} \end{array}\right) \tag{13}$$

for $t = 1, 2$.

The solution in (13) equates the marginal cost of borrowing an additional dollar in each market, r_t, to the marginal benefit in terms of larger reserve holdings and, possibly, an improved LCR position. The two max operators are present to account for four distinct situations banks may face:

(a) If $r_2 = r_1 = r_R$, there is no cost to the bank of improving both its reserve position and its LCR position by borrowing in the two interbank markets and holding the funds as excess reserves. In this case, the bank's problem is solved by any trading plan $\left\{\Delta_t^i\right\}$ that ensures the bank will not need to borrow from the central bank for any realization of ε^i.

(b) If $r_2 = r_1 > r_R$, a bank can costlessly improve its LCR position by borrowing in the term market and lending the same amount overnight, but borrowing in either market and holding the funds as excess reserves is costly. In this case, the solution given in (13) will have $E^i_R \leq E^i_{LCR}$, as depicted in panel (i) of Figure 4, and will have $G\left[E^i_R\right] < 1$. The bank will then face a positive probability of needing to borrow from the central bank to meet its reserve requirement, but not its LCR requirement.

(c) If $r_2 > r_1 = r_R$, the bank can costlessly improve its reserve position by borrowing overnight and holding the funds at the central bank, but borrowing at term to improve its LCR position is costly. In this case, the solution in (13) will have $E^i_{LCR} < E^i_R$, as in panel (ii) of Figure 4, and these values will be chosen so that $G\left[E^i_{LCR}\right] < 1$, but $G\left[\hat{\varepsilon}^i\right] = 1$. The bank will then face a positive probability of needing to borrow from the central bank to meet its LCR requirement, but not its reserve requirement.

(d) If $r_2 > r_1 > r_R$, it is costly for the bank to improve either its reserve or its LCR position through interbank trading. In this case, (13) implies that the solution will again have $E^i_{LCR} < E^i_R$ as depicted in panel (ii) of Figure 4, but the bank will now set these levels small enough that $G\left[\hat{\varepsilon}^i\right] < 1$. The bank's borrowing from the central bank will then be driven by the LCR requirement for some realizations of ε^i and by the reserve requirement for others.

In case (d), there is a unique pair of interbank trades $\left\{\Delta^i_t\right\}$ that solve the problem in (12). In the other three cases, there are many plans $\left\{\Delta^i_t\right\}$ that solve the problem, but all of these plans generate the same probabilities of needing to borrow from the central bank for the purpose of meeting the reserve requirement and for the purpose of meeting the LCR requirement. Notice that these probabilities are independent of the bank's initial balance sheet in Figure 1. In particular, even if a bank initially has abundant excess LCR liquidity, it will choose to trade to a position in which it is exposed to an LCR shortfall in some states of nature when $r_2 > r_1$ holds. Without loss of generality, we focus on symmetric outcomes in which banks trade to the same levels of excess reserves E^i_R and excess LCR liquidity E^i_{LCR} in cases where they are indifferent about one or both of these levels.

Given these common desired levels $\left(E^i_R, E^i_{LCR}\right)$, bank i's optimal trading activity will depend on its initial balance sheet in Figure 1 :

$$\Delta_1^i = E_R^i - \left(R^i - K^i\right) - \Delta_2^i \quad \text{and} \tag{14}$$

$$\Delta_2^i = \frac{1-\theta_D}{1-\theta_2}\left(E_{LCR}^i - \frac{B^i + R^i - \theta_D D^i}{1-\theta_D}\right). \tag{15}$$

Intuitively, we can think of each bank as trading in the term market as specified in (15) to move its excess LCR liquidity to the desired value E_{LCR}^i characterized in Proposition 1, and then trading in the overnight market as specified in (14) to move its excess reserves to the desired value E_R^i.

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,

$$\Delta_t \equiv \int_0^1 \Delta_t^i di = 0 \quad \text{for } t = 1, 2. \tag{16}$$

Substituting the individual demands (14) and (15) into (16) and using the result from Proposition 1 that all banks will choose to trade to the same levels of $\left(E_R^i, E_{LCR}^i\right)$, we can write the market-clearing equations as

$$E_R^i = R - K \equiv E_R \quad \text{and} \tag{17}$$

$$E_{LCR}^i = \frac{B + R - \theta_D D}{1-\theta_D} \equiv E_{LCR}. \tag{18}$$

The balance sheet variables with no superscript in these expressions indicate average levels in the banking system; for example, $K \equiv \int K^i di$ is the average reserve requirement across all banks. The right-hand side of (17) is thus the per-bank supply of excess reserves in the banking system. Similarly, the right-hand side of (18) is the amount of excess LCR liquidity available in the banking system, again expressed in per-bank terms. In other words, equilibrium in this model requires that interest rates adjust so that levels of excess reserves and excess LCR liquidity demanded each bank equal the average amounts available in the balance sheets in Figure 1. The critical value of the payment shock above which each bank's need to borrow from the central bank is driven by its reserve requirement when $E_{LCR} < E_R$ is then given by

$$\hat{\varepsilon} \equiv \frac{1-\theta_X}{\theta_D - \theta_X} E_R - \frac{1-\theta_D}{\theta_D - \theta_X} E_{LCR}. \tag{19}$$

The next proposition substitutes the market-clearing conditions (17) – (18) and the definition in (19) into Proposition 1 to derive the equilibrium interest rates $\{r_t^*\}$.

Proposition 2 *The unique equilibrium interest rate in market $t = 1, 2$ is given by*

$$r_t^* = r_R + (r_X - r_R) \begin{pmatrix} 1 - G\left[\max\left\{E_R, \hat{\varepsilon}\right\}\right] \\ +\frac{1-\theta_t}{1-\theta_X} \max\left\{G\left[\hat{\varepsilon}\right] - G\left[E_{LCR}\right], 0\right\} \end{pmatrix}.$$

Note that equilibrium interest rates in this model depend only on the balance sheet of the banking system as a whole and not on how resources are distributed across banks.[9]

4.4 The (re)distribution of excess LCR liquidity

In the absence of an LCR requirement, the only role of the interbank market is to allocate the given supply of excess reserves so that all banks face the same probability of a reserve shortfall at the end of the period. In such a setting, the term market is redundant and we can set $\Delta_2^i = 0$ for all i without any loss of generality. When the LCR requirement is introduced, however, the term market becomes essential for redistributing excess LCR liquidity so that all banks also face the same probability of experiencing a payment shock that leads to an LCR shortfall as well.

Through this endogenous redistribution of excess LCR liquidity, our model captures an important goal of the LCR: preventing the central bank from being the "lender of first resort" in a liquidity crisis (BCBS, 2013a). To see this link, suppose we extend the model to include an additional period. In this period, banks are again subject to deposit outflows, but a liquidity crisis occurs in which some bank(s) are excluded from the interbank market. Overnight loans from the pervious period must be repaid, but term loans remain in place. We show in the supplemental appendix that in the equilibrium with an LCR requirement, banks are on average in a better position to handle deposit outflows without having to borrow from the central bank (or sell illiquid assets). In this sense, imposing an LCR requirement in our model enhances financial stability as intended. Rather than focusing on these benefits using the extended model in more detail, we proceed with the baseline model to study the unintended consequences of the regulation for the implementation of monetary policy. In the next section, we ask how the introduction of an LCR requirement affects equilibrium interest rates. In Section 6, we then ask how the LCR requirement alters the effect of a central bank's open market operations and its ability to control market interest rates.

[9] If the model is expanded to include additional types of interbank loans, each with its own runoff rate θ_t, these additonal types will be redundant in equilibrium and the pricing equation in Proposition 2 will apply to the interest rate on *all* types of contracts. In this sense, our model with two types of contracts is without any loss of generality.

5 How the LCR affects interest rates

We begin this section by characterizing the conditions under which an LCR requirement does and does not affect equilibrium rates in our model. We then document the direction of the resulting changes and discuss their implications.

5.1 Interest rates when the LCR requirement is slack

In the absence of an LCR requirement, the equilibrium interest rate would be the same in both markets and would depend only on the supply of excess reserves to the banking system. Let r^P denote the standard interest rate from a Poole-style model, which is given by

$$r^P \equiv r_R + (r_X - r_R)(1 - G[E_R]). \tag{20}$$

This standard rate equals the interest rate paid by the central bank on excess reserves plus a *reserve premium* that measures the value of borrowing an additional dollar in helping the bank meet its reserve requirement. This reserve premium is proportional to the probability that the bank will experience a payment outflow ε^i larger than its equilibrium holding of excess reserves E_R. The next corollary establishes conditions under which the LCR requirement has no effect on equilibrium interest rates and, therefore, our results are equivalent to those from the standard model.

Corollary 3 *If* $E_{LCR} \geq E_R$ *or* $G[E_{LCR}] = 1$, *then* $r_2^* = r_1^* = r^P$.

This result shows that there are two situations in which the introduction of an LCR requirement has no effect. The first is when excess LCR liquidity in the banking system is larger than total excess reserves, in which case the equilibrium interest rates from Proposition 2 will lead banks to trade to the situation depicted in panel (i) of Figure 4. If this inequality is reversed and the situation is instead as depicted in panel (ii), the requirement will still have no effect if there is zero probability that the payment shock ε^i will be large enough to exhaust a bank's excess LCR liquidity.[10]

Note that the reserve premium in (20) can be either positive or zero, depending on the supply of excess reserves to the banking system. If this supply is large enough that $G[E_R] = 1$, the reserve

[10] The result in Corollary 3 depends on our assumption that the runoff rate for loans from the central bank is lower than that for deposits: $\theta_X < \theta_D$. If this equality is reversed, adding an LCR requirement can change equilibrium interest rates even when $E_{LCR} \geq E_R$ holds. See the supplemental appendix for details.

premium is zero and both equilibrium rates lie on the floor of the central bank's interest rate corridor at r_R. If, instead, the central bank sets the supply of excess reserves small enough that $G[E_R] < 1$, the reserve premium is positive and the common equilibrium interest rate in the two interbank markets lies in the interior of the corridor $[r_X, r_R]$. In Figure 5, we label these two cases as (a) and (b), respectively. The top row of the figure thus presents the two possible configurations of equilibrium interest rates when the conditions of Corollary 3 are met.

LCR requirement	Reserve requirement: slack ($G[\max\{E_R, E_X\}] = 1$)	Reserve requirement: binding ($G[\max\{E_R, E_X\}] < 1$)
slack ($E_{LCR} \geq E_R$ or $G[E_{LCR}] = 1$)	(a) $r_2^* = r_1^* = r_R$	(b) $r_2^* = r_1^* > r_R$
binding ($E_{LCR} < E_R$ and $G[E_{LCR}] < 1$)	(c) $r_2^* > r_1^* = r_R$	(d) $r_2^* > r_1^* > r_R$

Figure 5: Possible configurations of equilibrium interest rates

5.2 Interest rates when the LCR requirement binds

When the conditions of Corollary 3 are not met, the LCR requirement binds in the sense that a bank's equilibrium borrowing from the central bank is driven by its need to meet this requirement for some realizations of the payment shock ε^i. In this case, introducing liquidity regulation will change equilibrium interest rates. The next corollary documents the direction of these changes.

Corollary 4 *If $E_{LCR} < E_R$ and $G[E_{LCR}] < 1$, then $r_1^* < r^P$ and there exists $\bar{\theta} \in (\theta_X, 1)$ such that $r_2^* \begin{Bmatrix} < \\ = \\ > \end{Bmatrix} r^P$ as $\theta_2 \begin{Bmatrix} < \\ = \\ > \end{Bmatrix} \bar{\theta}$.*

A binding LCR requirement has two competing effects on an equilibrium interest rate r_t^*. On one hand, interbank borrowing becomes more valuable to the extent that it helps a bank meet the new requirement. On the other hand, the additional borrowing from the central bank associated with the new requirement implies that each bank is more likely to over-satisfy its reserve requirement; this fact makes borrowing reserves on the interbank market less valuable. Which of these two effects dominates depends on the runoff rate θ_t applied to the loan in the LCR calculation. In the overnight market, where the runoff rate is 100%, borrowing does not improve a bank's LCR position and the first effect is absent. As a result, the second effect necessarily dominates and liquidity regulation unambiguously lowers r_1^*. The same result will hold true for any loan type t with a sufficiently high runoff rate θ_t. If θ_t is close to zero, however, the first effect will dominate and introducing liquidity regulation will raise the equilibrium interest rate on these loans.

The result in Corollary 4 can also be seen by noting that when the LCR requirement binds, the equilibrium pricing equation in Proposition 2 can be written as

$$r_1^* = r_R + (r_X - r_R)\left(1 - G\left[\hat{\varepsilon}\right]\right) \tag{21}$$

$$r_2^* = r_1^* + (r_X - r_R)\frac{1-\theta_2}{1-\theta_X}\left(G\left[\hat{\varepsilon}\right] - G\left[E_{LCR}\right]\right). \tag{22}$$

The equilibrium overnight interest rate in (21) again equals r_R plus a reserve premium that measures the value of borrowing an additional dollar in this market for helping the bank meet its reserve requirement. Notice, however, that the reserve premium is now proportional to the probability that a bank's payment outflow is larger than the critical value $\hat{\varepsilon}$, rather than E_R as in (20). Under the conditions of Corollary 4, $\hat{\varepsilon} > E_R$ holds (see panel (*ii*) of Figure 4) and, hence, the introduction of an LCR requirement decreases the reserve premium.

The equilibrium term interest rate in (22) now equals the overnight rate plus an *LCR premium* that measures the value of borrowing an additional dollar at term for helping a bank meets its LCR requirement. This LCR premium is proportional to $G\left[\hat{\varepsilon}\right] - G\left[E_{LCR}\right]$, which is the probability that a bank's borrowing from the central bank will be driven by the LCR requirement (see again panel (*ii*) of Figure 4). The LCR premium is positive whenever the conditions of Corollary 4 hold.

The bottom row of Figure 5 lists the two possible configurations of equilibrium interest rates when the LCR requirement binds. In case (*c*), excess reserves are abundant and the reserve premium is zero even though the LCR premium is positive. Notice that the condition for the reserve premium to be zero is weaker when the LCR requirement binds ($G\left[\hat{\varepsilon}\right] = 1$) than when it is slack ($G\left[E_R\right] = 1$). Case (*d*) corresponds to a situation in which both the reserve premium and the LCR premium are positive.

5.3 Discussion

It is currently too early to reliably measure the empirical effects of introducing the LCR requirement on interbank interest rates because the new regulation is only partially in effect and, in addition, banks in many jurisdictions are holding very large quantities of central bank reserves as a result of unconventional monetary policies. Nevertheless, some evidence of LCR-related premia does exist. Boner and Eijffinger (2016) study bank-level balance sheet and interbank trading data from the Netherlands, which implemented a quantitative liquidity requirement similar in structure to the LCR in 2003. They show that banks facing a potential regulatory shortfall paid 10 basis points more on average for loans longer than 30 days than banks satisfying the requirement by a comfortable margin. In contrast, the two groups paid approximately the same rate to borrow overnight. While their result involves comparing the cross-section of banks and is based on a jurisdiction where high-quality liquid assets were in abundant supply, it nevertheless indicates that liquidity regulation can generate economically-meaningful premia in interbank interest rates.[11] We expect the effects we identify here to become more prominent over time as the regulation is fully phased in and as central banks unwind more of their unconventional policies.

6 Open market operations (OMOs) under the LCR

A central bank's monetary policy operations change the balance-sheet entries in Figure 1 and these changes, in turn, alter equilibrium interest rates through the relationships derived above. In this section, we show how the effects of an OMO can depend critically on the LCR position of the banking system as well as on the details of how the operation is structured. The structure of OMOs varies both within and across central banks along a number of dimensions. Prior to the financial crisis, for example, the Eurosystem operated primarily through collateralized loans of various maturities with banks as counterparties. The Federal Reserve, in contrast, used a combination of outright purchases and repurchase agreements with non-banks (the *primary dealers*) as counterparties. The assets used by the Federal Reserve as countervalue in their operations typically count fully toward HQLA under the LCR rules, while the Eurosystem has regularly used both HQLA and non-HQLA assets as countervalue. We ask how these different types of operations affect equilibrium interest rates in our model. To economize on notation, we focus on outright purchases/sales of assets,[12]

[11] More recently, Gete and Reher (2017) provide evidence of an LCR premium in the market for mortgage-backed securities (MBS). The LCR rules in the U.S. provide more favorable treatment of MBS issued by Ginnie Mae than by other goverment-sponsored enterprises in the calculation of HQLA. They show that an LCR premium has emerged on Ginnie Mae-backed securities and that this premium has affected relative lending standards and the quantities issued of different types of securities.

[12] In the supplemental appendix, we show that using repurchase agreements or collateralized loans can magnify the effects we identify here by a factor proportional to the size of the haircut used in the contract.

but we allow for the central bank's counterparties to be either banks or non-bank investors and we allow for operations using both bonds and/or loans as countervalue.

6.1 Balance sheet effects of an OMO

The central bank's operation occurs in stage I of our model (see Figure 2), before interbank markets open. Proposition 2 establishes that equilibrium interest rates depend only on the aggregate balance sheet of the banking system and not on bank-level variables. Figure 6 depicts the impact of an OMO on this balance sheet as well as on that of the central bank. Variables with a "0" subscript represent initial values, before the operation takes place. The central bank then buys (or sells, if negative) an amount z_B of bonds and z_L of loans. This operation changes the supply of reserves by $z \equiv z_B + z_L$.

Central Bank

Assets		Liabilities	
Loans	$L_0^{CB} + z_L$	Reserves	$R_0 + z$
Bonds	$B_0^{CB} + z_B$	Equity	Y^{CB}

Banking System

Assets		Liabilities	
Loans	$L_0 - \alpha_L z_L$	Deposits	$D_0 + (1-\alpha_L)z_L + (1-\alpha_B)z_B$
Bonds	$B_0 - \alpha_B z_B$		
Reserves	$R_0 + z$	Equity	Y

Figure 6: Balance sheet effects of an OMO

The effect of this operation on the balance sheet of the banking system depends on the central bank's counterparties. Let α_B and α_L denote the fraction of the bonds and loans, respectively, purchased from banks; the remaining fractions $(1-\alpha_B)$ and $(1-\alpha_L)$ are purchased from other investors. As the figure shows, when the central bank buys assets from banks, the total assets of the banking system do not change; banks hold more reserves but fewer bonds/loans. When the central bank buys assets from other investors, in contrast, these agents receive payment in the form of a bank deposit and both the assets and liabilities of the banking system increase.

Let E^0_{LCR} denote the initial level of excess LCR liquidity in the banking system. Straightforward algebra shows how an open market operation changes this value,

$$E_{LCR} = E^0_{LCR} + (1 - \alpha_B)\, z_B + \frac{1 - \theta_D\,(1 - \alpha_L)}{1 - \theta_D} z_L. \tag{23}$$

Note that the effect of a central bank purchase of either asset on E_{LCR} depends critically on who is selling the asset. If the central bank purchases bonds from banks ($z_B > 0$, $z_L = 0$ and $\alpha_B = 1$), for example, banks exchange one high-quality liquid asset for another and excess LCR liquidity remains unchanged. If it purchases bonds from non-bank investors ($\alpha_B = 0$), in contrast, excess LCR liquidity rises.

6.2 OMOs when the LCR requirement is slack

For reference, we first consider a situation in which initial excess LCR liquidity E^0_{LCR} is large enough that $E_{LCR} \geq E_R$ holds *after* the operation has taken place. As established in Corollary 3, this condition implies that the equilibrium interest rates in both interbank markets equal the rate that would prevail in the absence of liquidity regulation. Figure 7 plots this common equilibrium interest rate as a function of the size of the operation z for two different initial levels of excess reserves E^0_R. In both panels, the support of the payment shock is $\varepsilon^i \in [-2, 2]$ and initial excess LCR liquidity takes any value $E^0_{LCR} \geq 2$, which guarantees that the LCR requirement is slack for all values of z shown in the figure.[13]

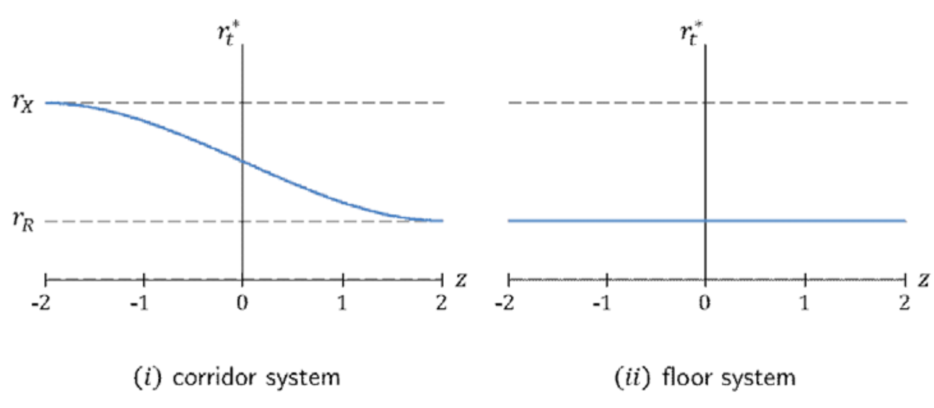

Figure 7: Effect of an OMO when the LCR requirement is slack

[13] The figure is created using a beta distribution for ε^i with parameters $\alpha = \beta = 2$. The runoff rate θ_D is set to 10%, the minimum standard for less-stable deposits in BCBS (2013b). Note that the runoff rates θ_t and θ_X have no effect in this figure because the LCR requirement is slack.

In panel (i), initial excess reserves E_R^0 are set to zero. Note that equilibrium interest rates lie at the midpoint of the corridor when excess reserves are zero after the operation ($z = 0$), a result that has been emphasized by Woodford (2001), Whitesell (2006) and others.[14] This panel represents the textbook effect of an open market operation when the central bank implements monetary policy using a *corridor system*. In a corridor system, the central bank aims to steer market interest rates to a point in the interior of its interest rate corridor $[r_R, r_X]$, often the midpoint. In practice, changes in *autonomous factors* (e.g., the quantity of bank notes in circulation, government deposits at the central bank, etc.) alter the initial supply of excess reserves E_R^0 and thereby shift this curve to the left/right. The position of the curve on a given day determines the size of the open market operation (i.e., the value of z) required to move market interest rates to the central bank's target.

In panel (ii) of Figure 7, initial excess reserves have been increased to $E_R^0 \geq 4$, which is large enough to ensure that the economy falls in case (a) of Figure 5 for all values of z shown in the figure. This panel represents a *floor system* of monetary policy implementation in which the central bank supplies enough excess reserves to drive the reserve premium to zero. In a floor system, the central bank controls short-term interest rates primarily by changing the interest rate it pays on excess reserves.[15] Given that the LCR requirement is slack, both r_1^* and r_2^* remain on the floor of the central bank's interest rate corridor as z varies.

Importantly, the two curves in Figure 7 apply for *any* type of open market operation as long as the LCR requirement is slack. The assets used in the operation and the central bank's counterparties have no effect on the resulting market interest rates. This result allows the central bank to choose the size of its open market operation based on monetary policy considerations, while the structure (counterparties, assets involved, etc.) can be chosen separately based, for example, on institutional or historical considerations.

6.3 OMOs when the LCR requirement binds

The patterns in Figure 7 can change dramatically when the LCR requirement binds for some values of z. Considering first the case of a corridor system, Figure 8 presents the effects of three different types of OMOs. In each case, initial excess reserves E_R^0 and initial excess LCR liquidity E_{LCR}^0 are

[14] This result obtains when the distribution of payment shocks satisfies $G(0) = 1/2$, which holds for any distribution that is symmetic around zero.

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

both zero.[16] The left-hand panel corresponds to an operation using only bonds ($z_B > z_L = 0$) with banks as counterparties $(\alpha_B = 1)$. Observe that the overnight rate is pushed rapidly towards the floor of the corridor when the central bank adds reserves ($z > 0$), while the term rate is unchanged at the midpoint of the corridor. This pattern illustrates the result in Corollary 4, with the overnight rate falling below the rate shown in Figure 7 while the term rate rises above it. To understand this pattern, 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 shortfall is thus unaffected by the operation, while the likelihood of it facing a reserve shortfall declines.

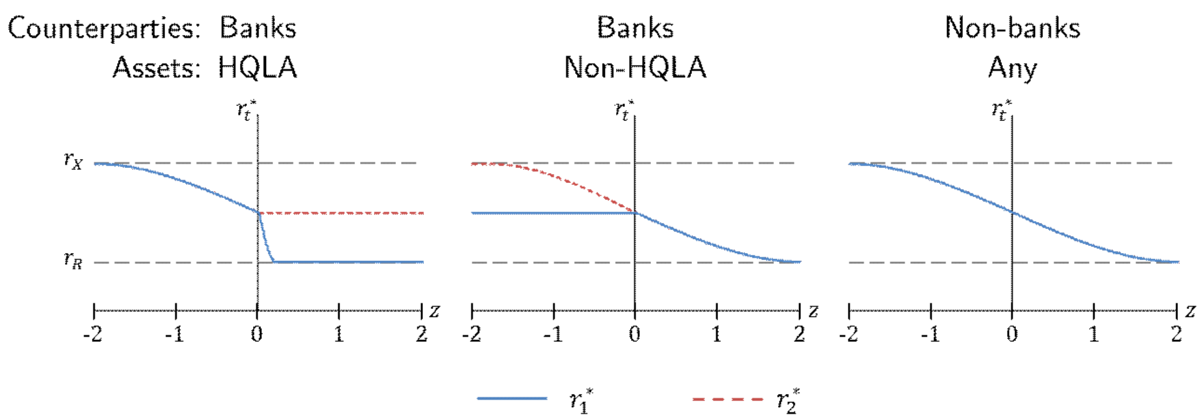

Figure 8: OMOs with a binding LCR in a corridor system

The center panel in Figure 8 presents the effects of an open market operation using only loans $(z_L > z_B = 0)$, again with banks as counterparties $(\alpha_L = 1)$. In this case, each dollar of assets purchased by the central bank increases excess reserves by a dollar, but increases excess LCR liquidity in (23) by more than a dollar. As a result, open market purchases ($z > 0$) now make the LCR requirement less binding while sales ($z < 0$) make it more binding, exactly the opposite of the previous case.

In the right-hand panel in Figure 8, the central bank's counterparties are non-bank investors $(\alpha_B = \alpha_L = 0)$. In this case, the type of asset used in the operation does not matter for equilibrium interest rates.[17] Open market purchases/sales now increases excess reserves and excess LCR liquidity by exactly the same amount, leaving their relative importance unchanged. Because parameter

[16] The runoff rate for term loans and for loans from the central bank are set to $\theta_2 = \theta_X = 0$ for this figure. All other parameter values are the same as in Figure 7.

[17] This fact can be seen by noting that when $\alpha_B = \alpha_L = 0$, excess LCR liquidity in (23) depends only on z and not on z_B and z_L separately.

values in Figure 8 are such that the LCR requirement is (barely) slack, this same situation holds for all values of z in the right-hand panel and the graph is identical to panel (i) of Figure 7.

Figure 9 presents the corresponding analysis when the central bank operates a floor system. Initial excess LCR liquidity E^0_{LCR} is set to zero as before, but initial excess reserves are now set to $E^0_R \geq 4$. These values imply that r^*_2 is at the midpoint of the corridor when $z = 0$ and that r^*_1 lies on the floor of the corridor for all values of z shown in the figure. The three panels in the figure represent the same types of operations as in Figure 8. In the left-hand panel, the central bank uses only bonds with banks as counterparties. As before, this type of operation does not change excess LCR liquidity in the banking system. Now that the reserve requirement is slack, this fact implies that the operation has no effect on the LCR premium and, hence, r_2 remains at the midpoint of the corridor for all values of z.

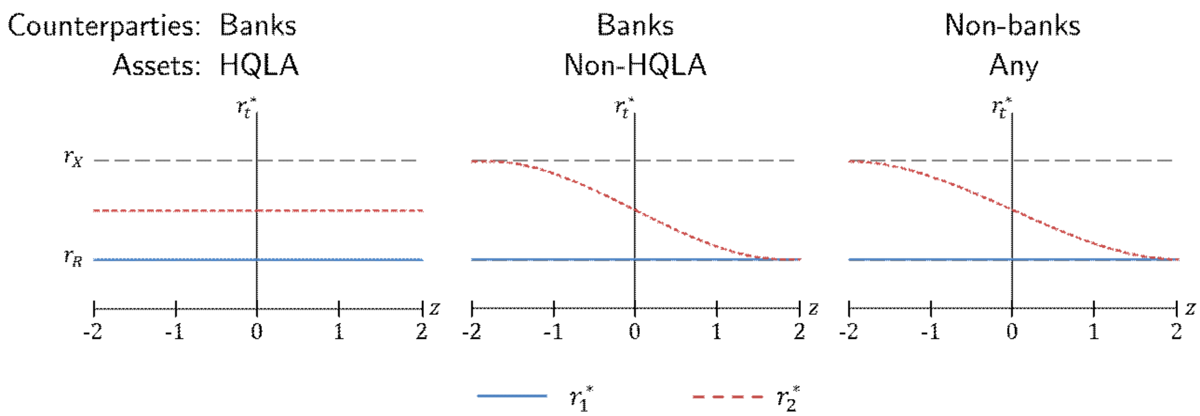

Figure 9: OMOs with a binding LCR in a floor system

When the operation instead involves loans with banks as counterparties, as in the center panel, central bank purchases increase excess LCR liquidity in (23) by replacing loans on bank balance sheets with reserves. As a result, the equilibrium LCR premium and r^*_2 decrease. Central bank sales of bonds ($z < 0$) have the opposite effect. The pattern is qualitatively similar when the central bank's counterparties are non-bank investors, as shown in the right-hand panel, but the mechanics are slightly different. In this case, a central bank purchase of any asset raises excess LCR liquidity in (23) by creating new reserves in the banking system financed by deposits. In both of these cases, it is interesting to note that OMOs can play a role in affecting market interest rates and economic activity even when the overnight interest rate lies at the floor of the corridor and is unresponsive to these operations.

6.4 Discussion

Taken together, Figures 8 and 9 show how the introduction of an LCR requirement can substantially alter the equilibrium effects of an OMO from the benchmark in Figure 7. When the central bank operates a corridor system, adding reserves may either increase the LCR premium or decrease it, depending on how the operation is structured. Similarly, the overnight rate may become more responsive to the size of the operation over some region or completely unresponsive. In a floor system, OMOs have no effect on the reserve premium, which is always zero, but may still affect market interest rates through the LCR premium. Whether or not the LCR premium changes again depends on operational details – types of counterparties and assets used – that have no effect on equilibrium interest rates in the absence of liquidity regulation. Moreover, these effects may be either large or nonexistent, depending on the initial LCR position of the banking system E^0_{LCR}.

Central banks will need to take the LCR premium into account in the conduct of monetary policy, since interest rates with terms of longer than 30 days are the most relevant for bank lending decisions, economic activity more generally and inflation. In addition, they will likely need to choose the size and structure of an operation jointly in order to achieve a particular outcome. For example, a central bank operating a corridor system might find operations with non-bank counterparties to be the most effective if the LCR requirement is currently slack, since such operations will keep the LCR premium at zero. If the LCR requirement currently binds, however, the central bank may prefer to use banks as counterparties and thereby influence the LCR premium. For a central bank using a floor system, operations using non-HQLA or with non-bank counterparties may be the most desirable, as they allow the central bank to influence the LCR premium and term interest rates. In general, as Figures 8 and 9 illustrate, the design features of the operation can be every bit as important for determining equilibrium interest rates as the changes in the supply of excess reserves.

To further complicate matters, some of these design features may not be fully controlled by the central bank. The parameters α_B and α_L in our model reflect the degree to which the central bank's direct counterparties in the operation are banks. In reality, however, an OMO may bring about other trades in asset markets. The effect of the operation on market interest rates will depend on the extent to which the *net* sellers/buyers of the assets involved are banks. For example, the Federal Reserve's counterparties have historically been (non-bank) primary dealers, which would seem to indicate $\alpha_B = 0$ when the Fed purchases bonds, for example. However, these dealers may at the same time be purchasing bonds from others agents to maintain a balanced inventory. To the extent that dealers' purchases come from banks, the effective value of α_B would be positive. Seen this way, not only are the parameters α_B and α_L not directly chosen by the central bank, they may also be unknown when the operation takes place. While such trade in asset markets is outside the scope of our model, our analysis indicates that forecasting the effect of a particular operation on market interest rates may become substantially more difficult with an LCR requirement in place.

7 Concluding remarks

Prior to the global financial crisis, many central banks had gradually developed operational frameworks based on reserves and open market operations that allowed them to control banks' marginal funding costs, at least for relatively short maturities, with a high degree of precision. After the crisis, some of these central banks – including the Federal Reserve and the European Central Bank – have moved away from these frameworks toward more unconventional measures because of the effective lower bound on nominal interest rates. As the stance of monetary policy begins to normalize and unconventional policies are unwound, these central banks may seek to return to more conventional frameworks. The environment in which they will operate, however, will differ from the pre-crisis period because the Basel III liquidity regulations will be either partially or fully in effect.

When the LCR requirement binds, banks' funding cost at any maturity of longer than 30 days is determined, at least in part, by the quantity of high-quality liquid assets in the banking system rather than the quantity of central bank reserves. Our analysis has shown how this fact has important implications for both the level of equilibrium interest rates and the impact of a central bank's operations. Our results indicate that if a central bank were to simply resume its pre-crisis operational procedures, it may have significant difficulty controlling market interest rates. At a minimum, central banks will need to monitor the LCR of the banking system in much the same way as they have traditionally monitored other factors that affect interbank markets. They may also wish to adjust their operational frameworks for implementing monetary policy to better match the new environment; the model we study here may provide a useful starting point for identifying effective adjustments.

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