ESSAYS ON MONETARY POLICY, SAFE ASSETS, AND THE REPO MARKET

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Part I

Introduction

Summary of Research Results

This dissertation analyzes topics related to unconventional monetary policy, safe assets, short-term funding, and the market for repurchase agreements.

In the first research paper, we propose and test a new channel that links funding liquidity risk and interest rates in short-term funding markets. Unlike existing theories that focus on premia demanded by lenders, the funding liquidity risk channel postulates that borrowers exposed to liquidity shocks are willing to pay a markup for immediate funding. We test and quantify the channel using unique trade-by-trade data and uncover systematic differences across individual banks' funding cost driven by idiosyncratic liquidity risk. These differences are persistent over a decade, suggesting that the funding liquidity risk channel is relevant in general and not only arises during crisis times.

The second research paper focuses on the effect of Quantitative Easing (QE) on financial stability. At least since the European Sovereign Debt Crisis 2009−2012, the credit risk of euro area sovereigns affects the financial health of their banking sectors and vice versa, creating an adverse feedback loop known as "sovereign-bank nexus". We show that QE can effectively mitigate the sovereign-bank nexus. Our results indicate that the European Central Bank's (ECB) Public Sector Purchase Programme (PSPP) reduced the co-movement of sovereign and bank credit risk by almost 80%. The mitigation is driven by the euro area periphery and works through three channels: (i) a reduction in government bond holdings of banks, (ii) an increase of government bond prices, and (iii) an increase in excess liquidity holdings of banks.

The massive recourse to QE calls for a better understanding of its effects on safe assets. In the third research paper, we show how QE impacts the total amount, cross-sectional distribution, and composition of safe assets in the economy. To this end, we develop a simple balance sheet model and analyze the interaction between the PSPP and safe assets empirically. We find that the amount of universally accessible safe assets decreases and that there is a transfer of safe assets from the non-bank to the banking sector. We call this phenomenon the *safe asset illusion*. The sectoral shift in the holding structure of safe assets has important implications for financial stability and the cost of secured liquidity.

Finally, in the fourth research paper, we provide a new explanation for the interaction between QE and short-term interest rates. Since the onset of the PSPP in the euro area in March 2015, short-term rates began to diverge and partially fell below the ECB's deposit facility rate. We show that these interest rate movements are driven by a joint supply and demand shock creating a *scarcity premium* for money market rates backed by high-quality collateral. Purchasing 1% of the outstanding government bonds is associated with a 1.0−1.7 basis points increase of the scarcity premium because the supply of collateral decreases (supply channel) and an additional 1.6−2.8 basis points increase in the premium because the additional liquidity increases the demand for collateral (demand channel).

Zusammenfassung der Forschungsergebnisse

Die vorliegende Dissertation behandelt aktuelle Themen zu unkonventioneller Geldpolitik, sicheren Vermögenswerten (safe assets), Finanzmarktliquidität und Rückkaufvereinbarungen.

Im ersten Forschungspapier untersuchen wir den Zusammenhang zwischen Liquiditätsrisiken und kurzfristigen Zinsen. Im Gegensatz zu bestehenden Theorien, die sich auf die von Kreditgebern geforderten Prämien konzentrieren, fokussieren wir uns auf Kreditnehmer und zeigen, dass diese bereit sind einen Aufschlag für eine sofortige Finanzierung zu zahlen. Wir testen und quantifizieren diesen Effekt und decken systematische Unterschiede zwischen den Refinanzierungskosten einzelner Banken auf. Diese Unterschiede bleiben über ein Jahrzehnt hinweg bestehen, was darauf hindeutet, dass der von uns untersuchte Zusammenhang nicht nur in Krisenzeiten relevant ist.

Das zweite Forschungspapier analysiert den Effekt von Quantiativer Lockerung (Quantitative Easing, kurz: QE) auf die Finanzstabilität. Spätestens seit der europäischen Staatsschuldenkrise 2009−2012 wirkt sich das Kreditrisiko des Staates auf die finanzielle Stabilität des Bankensektors aus und umgekehrt. Dadurch entstehen negative Rückkopplungseffekte, die als "Sovereign-Bank-Nexus" bekannt sind. Wir zeigen, dass QE den Sovereign-Bank-Nexus abschwächen kann. Unsere Ergebnisse deuten darauf hin, dass das Programm der Europäischen Zentralbank (EZB) zum Ankauf von Staatsanleihen (Public Sector Purchase Programme, kurz: PSPP) die Korrelation von Staats- und Bankkreditrisiko um fast 80% reduziert hat.

Der massive Rückgriff auf QE erfordert ein besseres Verständnis der Auswirkungen auf sichere Vermögenswerte (safe assets). Im dritten Forschungspapier zeigen wir, wie sich QE auf die Gesamtmenge, die Verteilung und die Zusammensetzung von sicheren Vermögenswerten auswirkt. Zu diesem Zweck entwickeln wir ein Bilanzmodell und führen eine empirische Analyse der Auswirkungen des PSPPs auf sichere Vermögenswerte durch. Wir stellen fest, dass die Menge an allgemein zugänglichen sicheren Vermögenswerten abnimmt und dass es einen Transfer von sicheren Vermögenswerten aus dem Nicht-Bankensektor in den Bankensektor gibt. Wir nennen dieses Phänomen die "Safe Asset Illusion". Die Safe Asset Illusion hat wichtige Implikationen für die Finanzstabilität und die kurzfristigen Refinanzierungskosten von Banken.

Im vierten Forschungspapier präsentieren wir eine neue Erklärung für die Interaktion zwischen QE und kurzfristigen Zinsen. Seit dem Beginn des PSPPs im März 2015 sind kurzfristige Zinsen divergiert und teilweise unter den Zins der Einlagefazilität der EZB gefallen. Wir zeigen, dass diese Zinsbewegungen durch einen gemeinsamen Angebots- und Nachfrageschock getrieben sind, der eine Knappheitsprämie erzeugt. Der Kauf von 1% der ausstehenden Staatsanleihen durch die EZB ist mit einem Anstieg der Knappheitsprämie um 1,0−1,7 Basispunkte verbunden, weil das Angebot an Sicherheiten sinkt (Angebotskanal); gleichzeitig steigt die Knappheitspärmie um 1,6−2,8 Basispunkte, weil die zusätzliche Liquidität die Nachfrage nach Sicherheiten erhöht (Nachfragekanal).

Part II

Research Papers

Liquidity Risk and Funding Cost

Alexander Bechtel, Angelo Ranaldo, and Jan Wrampelmeyer

Abstract

We propose and test a new channel that links funding liquidity risk and interest rates in short-term funding markets. Unlike existing theories that focus on premia demanded by lenders, the funding liquidity risk channel postulates that borrowers exposed to liquidity shocks are willing to pay a markup for immediate funding. We test and quantify the channel using unique trade-by-trade data and uncover systematic differences across individual banks' funding cost driven by idiosyncratic liquidity risk. These differences are persistent over a decade, suggesting that the funding liquidity risk channel is relevant in general and not only arises during crisis times.

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1. Introduction

Funding illiquidity arises when solvent but illiquid financial institutions are unable to obtain refinancing. Banks are particularly sensitive to funding illiquidity because maturity transformation—that is, funding long-term assets with short-term liabilities—is at the core of their business model. We propose a new channel that outlines how funding liquidity risk impacts interest rates in short-term funding markets—the funding liquidity risk channel. In extant literature, interest rate or yield spreads are usually attributed to premia required by lenders as compensation for default risk and market illiquidity.[1] In the funding liquidity risk channel, we turn this rationale upside down. We show that borrowers have a higher willingness to pay for liquidity if they are exposed to liquidity shocks. We test and quantify the channel and reveal systematic heterogeneity across banks' liquidity risk, their willingness to pay for immediate access to liquidity, and hence their funding cost. This heterogeneity is persistent over more than ten years, suggesting that the channel is related to liquidity management in general and not only arises during crisis times.

Figure 1 motivates our novel perspective. It depicts the average overnight funding costs of individual borrowers in the main segment of the European interbank funding market, the central-counterparty (CCP)-based European repo market.[2] In this market—which is similar to the GCF repo market in the U.S.—lenders cannot ask for risk premia specific to borrowers because trading is anonymous and centrally cleared. Despite anonymity and central clearing, Panel (a) reveals that there is significant heterogeneity in the average funding costs of individual banks. Some banks pay systematically more than others for their overnight funding. Panel (b) illustrates that these differences are persistent and exhibit considerable time variation on a monthly basis of up to 10 basis points on average. In times of crisis, daily spreads between banks with high and low funding cost even reach up to 50 basis points. This is remarkable,

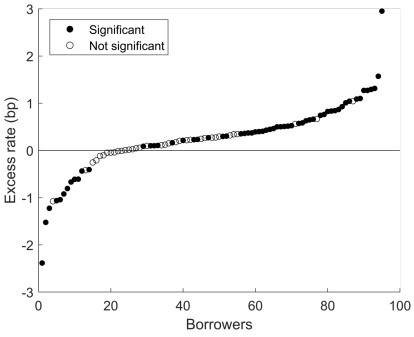
[1] If borrowers are more likely to default or if markets are illiquid, lenders demand higher rates of return. A large body of literature examines these premia in interbank markets (e.g., Michaud and Upper, 2008; Taylor and Williams, 2009; Filipovic and Trolle, 2013), corporate bond markets (e.g., Longstaff, Mithal, and Neis, 2005; Chen, Lesmond, and Wei, 2007; Friewald, Jankowitsch, and Subrahmanyam, 2012), and sovereign bond markets (e.g. Beber, Brandt, and Kavajecz, 2009; Krishnamurthy and Vissing-Jorgensen, 2012).

[2] The CCP-based European repo market is the largest market for euro interbank funding with a quarterly turnover of more than EUR 5.5 trillion (European Central Bank, 2015). A repurchase agreement, short repo, is a contract that stipulates the purchase and repurchase of a security. The repo buyer purchases the asset (mostly fixed-income securities) from the seller and commits to sell it back at a predetermined price in the future. The difference between purchase and repurchase price determines the repo rate. The buyer effectively lends cash to the seller, which makes repos economically identical to collateralized loans. We explain the features of this market in detail in Section 4.

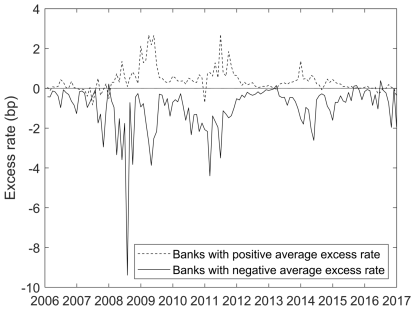
given the short maturity of these loans and the fact that the CCP-based repo market is one of the most liquid segments of the euro money market, populated by sophisticated market participants. The magnitude of these interest rate spreads within a single segment of the euro money market is comparable to spreads across different segments in the U.S. money market, which range from 3–5 basis points in calm periods to 20–50 basis points in times of crisis (Duffie and Krishnamurthy, 2016).

Figure 1: Heterogeneous funding costs

Panel (a) of Figure 1 presents for each borrower the average daily overnight repo rate paid in excess of the volume-weighted market average rate. In other words, it shows the average additional borrowing costs paid by each bank compared to the market average. Banks on the x-axis are ordered according to their performance. The filled black circles denote statistical significance at the 5% level. One outlier at 8.4 basis points is omitted. Panel (b) depicts the time variation of the banks with a significant positive and negative average excess rate, that is, those above and below the solid vertical line in Panel (a).



(a) Cross-section of average excess rates



(b) Excess rates of banks with positive and negative average excess rates

We show that it is the exposure of banks to idiosyncratic funding liquidity risk that drives the heterogeneity presented in Panel (a) of Figure 1. In addition, we find that certain banks are systematically and persistently more exposed to funding liquidity risk and that this explains the persistence of the heterogeneity presented in Panel (b). We build a simple model of the funding liquidity risk channel and provide empirical evidence using a unique trade-by-trade data set of funding transactions from 2006 to 2016. In the model, liquidity risk arises from the exposure of banks to liquidity shocks that need to be balanced urgently. In practice, the demand for immediate funding could arise due to, for example, transactions in real-time payment systems, margin calls, or funding that must be obtained until the end of the trading day. Banks differ in their liquidity risk due to the amount of liquidity buffer they have available, their liquidity management capabilities, or the nature of their business models. Being heavily exposed to time-sensitive liquidity shocks makes it difficult to manage short-term funding in a forward-

looking manner. Therefore, banks with high liquidity risk act more aggressively by demanding the immediate execution of their trades. This leads to higher interest rates and, hence, higher funding costs for these banks.

In our empirical analysis, we provide evidence for the funding liquidity risk channel and quantify the markup that borrowers pay due to funding liquidity risk. Three major identification challenges arise: First, we must isolate funding transactions from transactions with other intentions, such as market making, speculation, arbitrage trading, or sourcing a specific security. Second, we must construct a measure for the idiosyncratic funding liquidity risk of borrowers. Finally, we must isolate the markup a borrower is willing to pay due to its liquidity risk from the premia demanded by lenders. We overcome these challenges by exploiting the institutional design of the European interbank funding market, including anonymous electronic trading and central clearing.

We find that borrowers with high liquidity risk pay, on average, two basis points more for their daily funding than their low-risk peers. This markup is comparable in magnitude to the credit risk premium demanded by lenders in the unsecured interbank money market as documented by Angelini, Nobili, and Picillo (2011). In light of the large daily transaction volumes in interbank funding markets—the average bank borrows EUR 617 million per day—these results are economically meaningful. An increase of one standard deviation in liquidity risk increases the nominal costs of short-term funding by over 2.5%. The costs are three times higher during crises compared to times of high excess liquidity, implying that central banks can mitigate the channel by increasing the size of their balance sheet. The lender perspective is completely consistent with what we find for borrowers in the sense that revenues are heterogeneous and driven by liquidity risk. In particular, in the lender analysis, we are able to show that our market design enables us to control for credit risk and that our results are indeed driven by funding liquidity risk.

Besides relying on the market design of the European interbank funding market to get a clean identification, we test for various alternative explanations and address omitted variable concerns. For instance, we are able to rule out that our estimates of the liquidity risk markup are contaminated by credit risk. To this end, we examine the pricing and trading behavior of banks when lending. If our results were driven by credit risk, they should become insignificant when looking at lenders because credit risk only affects borrowing rates. In line with the funding liquidity risk channel, we find that lenders with higher liquidity risk receive lower rates. We run a battery of additional robustness checks to support the validity of our measure and rule out other alternative narratives that might explain our results. Finally, we follow the methodology of Oster (2019) to bound the potential bias in our estimate of the liquidity risk markup arising from unobserved variables. We find that our quantification of the liquidity risk markup is robust to the presence of unspecified omitted variables.

Our results are important for at least three reasons. First, the funding liquidity risk channel

provides a new explanation for how funding liquidity risk affects interest rates in short-term funding markets. These interest rates play a central role in financial markets, for example, as monetary policy target and benchmark for trillions of derivative contracts. Our results indicate that measuring and interpreting interest rate spreads without considering the funding liquidity risk channel can be misleading. Decomposing interest rates into premia demanded by lenders and markups paid by borrowers is important to enable regulators and central banks to develop effective policies. For example, it facilitates the distinction between insolvent and illiquid banks, which require different policy responses.

Second, the funding liquidity risk channel provides an explanation for the systematic and persistent heterogeneity in funding costs. Systematic differences in short-term funding rates can undermine efficient liquidity allocation and the pass-through of monetary policy (Duffie and Krishnamurthy, 2016). Gambacorta and Shin (2018) show that higher funding costs translate into less intermediation activity, thereby weakening the transmission of monetary policy. Moreover, systematic heterogeneity can be the result of inefficiencies in the liquidity management of banks. Such inefficiencies can lead to incorrect measurements of costs, returns, and risks in numerous aspects of banks' business and trading activities, for example, through liquidity transfer pricing and funding value adjustments (BCBS, 2008). Hence, banks might pass-through the resulting differences in funding costs to their clients, thereby causing heterogeneity to spread outside the funding market.

Third, funding liquidity risk is key for financial stability. It can reinforce market illiquidity (Brunnermeier and Pedersen, 2009) and create a transmission channel between market illiquidity and credit risk (He and Xiong, 2012). These concerns become even more important in light of the transition to real-time payment systems. The need to settle payments immediately creates additional challenges for the liquidity management of banks and could potentially be a new source of financial instability. Thus, understanding the origins and dynamics of funding liquidity risk is crucial for regulators that aim to maintain financial stability and curtail the liquidity risk of banks (for example, Basel III and the Dodd-Frank Act).

The paper proceeds as follows. In Section 2, we provide an overview of the literature and how we contribute to it. Section 3 presents the intuition behind the funding liquidity risk channel as well as a simple theoretical model. In Section 4, we provide empirical evidence for the channel. Section 5 addresses omitted variable concerns. Section 6 discusses the policy implications of our findings and Section 7 concludes.

2. Literature

This paper contributes to four strands of the literature: First, prior research on interest rate spreads in short-term debt markets suggests that interest rates deviate from the risk-free rate because lenders require a compensation for default and non-default risks (e.g., Afonso, Kovner,

and Schoar, 2011; Acharya and Skeie, 2011; Filipovic and Trolle, 2013; Schwarz, 2019). The former usually refers to credit risk and the latter to market illiquidity. Imbierowicz and Rauch (2014) and Morris and Shin (2016) point out that funding liquidity risk is an important component of banks' default risk. We are the first to find that funding liquidity risk is priced within interest rates through a *borrower* markup instead of (only) through a risk premium required by lenders. We provide a new explanation, that is the funding liquidity risk channel, outlining that borrowers are willing to pay a markup due to their exposure to funding liquidity risk. To the best of our knowledge, none of the previous studies identifies and quantifies this channel.

Second, we extend the literature on short-term funding markets, which have so far mostly been studied at aggregate levels or with a focus on specific market segments in distressed periods.[3] We contribute to this literature by adopting a broader and, simultaneously, more granular perspective. Our perspective is broader because we consider crisis and non-crisis periods, which is an approach that provides valuable information regarding how funding markets function in different regimes. Simultaneously, our perspective is more granular because we analyze the behavior of individual banks instead of only market aggregates.

Other papers analyze individual banks' willingness to pay for liquidity, but at central bank auctions (e.g., Bindseil, Nyborg, and Strebulaev, 2009; Fecht, Nyborg, and Rocholl, 2011; Drehmann and Nikolaou, 2013; Cassola, Hortacsu, and Kastl, 2013). We expand on this literature in three respects: (1) We identify and quantify the link between the liquidity risk of individual banks and their funding costs. By analyzing individual banks rather than the aggregate market, we reveal significant heterogeneity across funding costs of banks due to differences in exposure to liquidity shocks. (2) We provide a comprehensive analysis and consistent explanation of individual banks' borrowing *and* lending behavior across different tenors and collateral. (3) We analyze the willingness to pay on a daily basis over a much longer sample period than the existing literature, finding that banks' willingness to pay for liquidity is persistent over calm and crisis times and different monetary policy regimes.

Third, we contribute to the literature on the microstructure of short-term funding markets as our liquidity risk measure is based on the demand for immediacy of execution. There is a long history of theoretical and empirical research on trading immediacy (e.g., Demsetz, 1968; Foucault, Kadan, and Kandel, 2005; Large, 2009) and limit order book markets (e.g., Glosten, 1994; Biais, Hillion, and Spatt, 1995). Grossman and Miller (1988) present a model in which agents that are hit by liquidity shocks face a trade-off between trading with counterparties that arrive later and trading immediately with the market maker. There are very few studies on

[3]See Bartolini et al. (2011), Gorton and Metrick (2012), Krishnamurthy, Nagel, and Orlov (2014), and Copeland, Martin, and Walker (2014) for the U.S. and Mancini, Ranaldo, and Wrampelmeyer (2016) and Boissel et al. (2017) for Europe.

the microstructure of short-term funding markets.[4] Our study is the first to analyze the order submission of individual banks in the repo market and provides empirical evidence that liquidity risk increases the demand for immediate funding. It should be stressed that the functioning of the repo market is very different from that of equity markets studied in previous literature. As we will discuss in more detail in Section 4, rather than market making, speculation, and arbitrage, the predominant reason to trade in the General Collateral (GC) repo market is to borrow or lend cash (and not collateral) to fulfil idiosyncratic liquidity needs. Apart from liquidity management issues, market participants are not exposed to information asymmetry and counterparty credit risk. As predicted by our theoretical model accommodating all these features, we provide empirical evidence that liquidity risk increases the demand for immediate funding.

Lastly, we contribute to the empirical banking literature in general by deriving and using a high-frequency measure of funding liquidity risk at the bank level. In extant literature, funding liquidity risk is usually measured at the aggregate level via money market spreads such as the Libor-OIS spread. However, these measures tend to be affected by various other risk factors (e.g., Gyntelberg and Wooldridge, 2008). Similarly, the aggregate measure of Drehmann and Nikolaou (2013) based on banks' willingness to pay at central bank auctions is confounded by credit risk and strategic bidding behavior (see Cassola, Hortacsu, and Kastl, 2013). Moreover, auction-based measures are not applicable in periods when central banks supply unlimited quantities of liquidity, such as during the ECB's fixed-rate, full allotment regime since 2008. Previous bank-level studies use balance sheet information that is available only on an annual or quarterly frequency (e.g., Cornett et al., 2011; Angelini, Nobili, and Picillo, 2011; Bai, Krishnamurthy, and Weymuller, 2018). In contrast, our measure is market-based and available at a daily frequency.

3. Funding liquidity risk channel

This section introduces the intuition underlying the funding liquidity risk channel. We provide a simple theoretical model to illustrate why borrowers with high liquidity risk are willing to pay a markup to lock in their funding.

3.1 Intuition and preliminary evidence

In general, funding liquidity risk emerges from a liquidity mismatch between assets and liabilities. Banks fund long-term assets with short-term liabilities. Relying more heavily on volatile sources of funding—for example, deposits from a fickle customer base or short-term interbank

[4] An exception for the U.S. is Furfine (1999), who examines the market microstructure of the federal funds market. Baglioni and Monticini (2008) and Abbassi, Fecht, and Tischer (2017) analyze intraday pricing patterns of European unsecured and repo rates, respectively.

lending—exposes banks to regular liquidity shocks. During the day, these shocks can take various forms, such as payments to large-value payment systems, unexpected deposit withdrawals, margin calls, clients' drawing upon credit lines, or contingent payments related to a failure of a payment and settlement system (BCBS, 2013).

Funding liquidity risk is the risk of a liquidity shock leading to a binding funding constraint. In such a scenario, a bank needs to obtain funding quickly in order to balance its liquidity position before payments are settled. An urgent funding need can, for instance, arise in real-time gross settlement systems, where cash is transferred transaction-by-transaction in real time. Alternatively, margin calls can cause payment obligations on short notice. Lastly, lenders may not rollover their funding, such that banks must obtain funding until the end of the trading day to avoid having to resort to the standing facilities of the central bank.

Banks differ in their liquidity risk due to the amount of liquidity buffer they have available, their liquidity management capabilities, or the nature of their business models. Banks with a larger liquidity buffer can be more patient in obtaining funding once hit by a shock because the payment can be fulfilled using the liquidity buffer. Similarly, if banks are good at anticipating borrowing requirements, they can manage their liquidity in a manner that avoids funding constraints and the urgent need to borrow. Lastly, the business model and client base affect the size of shocks and the immediacy with which they need to be balanced in the interbank market.

Banks with high funding liquidity risk are more likely to demand immediacy of execution in the interbank market. Our model follows the literature on limit order book markets and shows that demanding immediacy increases funding cost. In a limit order book market, banks can choose between submitting market orders and limit orders. A market order guarantees the immediate execution of a trade at the best price available upon the order arrival. On the other hand, a limit order enables the trader to improve the execution price. However, the execution of a limit order is neither immediate nor certain. Consequently, banks face a trade-off between the cost of immediacy and the expected cost of delayed or no execution.[5] High funding liquidity risk implies being exposed to payment shocks that need to be urgently balanced, such that the expected cost of delayed execution is relatively high. Therefore, banks with high funding liquidity risk are likely to demand immediacy, implying that they use market orders to lock in their funding. This increases funding costs, as market orders are more costly than limit orders.

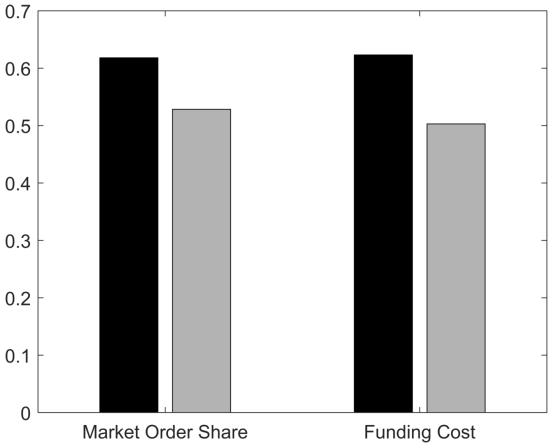
Figure 2 provides some preliminary empirical evidence for the link between funding liquidity risk, the demand for immediacy, and funding cost. It plots the average market order shares and funding costs for banks with high and low funding liquidity risk. We measure the funding liquidity risk of banks via their reliance on short-term wholesale funding. The black (grey) bars illustrate average market order shares and funding costs of bank-year observations with funding

[5]This trade-off was first examined by Demsetz (1968) and is at the center of more recent work on limit order book markets, such as Foucault, Kadan, and Kandel (2005), Rosu (2009), and Large (2009).

liquidity risk above (below) the median.

Figure 2: Funding liquidity risk channel intuition

Figure 2 shows the average market order shares and funding costs for banks with high and low funding liquidity risk. The black (grey) bars illustrate average market order shares and funding costs of bank-year observations with funding liquidity risk above (below) the median. We measure funding liquidity risk via the share of short-term (less than one year) wholesale over total wholesale funding. We measure funding costs as the relative frequency of paying a positive excess rate. More precisely, a relative frequency of 0.5 implies that banks pay more than the daily volume-weighted average repo rate in 50% of their trades. In our empirical analysis, we mainly use the excess rate directly as a measure for funding cost. For illustrative purposes, the relative frequency is better suited here because it is between 0 and 1 by construction. We introduce this measure more thoroughly in our empirical analysis.



In line with the funding liquidity risk channel, banks with high funding liquidity risk have a significantly higher demand for immediacy as indicated by their market order share. Simultaneously, these banks also have significantly higher funding costs. In the Internet Appendix, we run a pooled panel regression to show that the relation between funding liquidity risk and market order shares as well as funding costs is statistically and economically significant. A 10% increase in the share of short-term wholesale funding leads to a 2.1% increase in the market order share of banks and a 2.3% increase in funding costs.

It is important to note that the funding liquidity risk channel consistently applies to the lending business of banks because liquidity shocks can be either positive or negative. A positive liquidity shock leaves a bank with a funding surplus. Similar to the deficit case, such a bank must balance its books to avoid high opportunity costs. If it fails to do so until the end of the trading day, it must deposit the excess liquidity at the central bank, thereby lowering the return. Hence, banks with high liquidity risk have an incentive to demand immediacy and, thus, accept lower interest rates to avoid having to resort to the central bank. Our model,

presented in the next section, provides a clear representation of how the funding liquidity risk channel works for borrowing and lending. For the sake of brevity, the empirical analysis mainly focuses on negative liquidity shocks and borrowing. We examine the lending business of banks in Section 5.1.

3.2 Theoretical model

Setup

In order to theoretically highlight the funding liquidity risk channel, we present a simple model of limit order book markets with continuous trading based on Foucault, Pagano, and Röell (2013). We focus on the interbank market, in which banks can manage their short-term funding needs during the course of the day.[6] The interbank market is structurally different from the equity market, so we cannot directly apply all concepts from the literature on equity markets. For instance, given that the asset traded is cash, there is no asymmetric information about the fundamental value of the asset. Thus, there is no natural distinction between uninformed liquidity traders and liquidity providers that are better informed. Our model fits into a wider framework of monetary policy implementation in the tradition of Poole (1968). Before entering the interbank market to manage their own liquidity deficit or surplus, banks receive liquidity from the central bank. Incoming payment shocks after the central bank's liquidity allocation create the need for interbank trading (e.g., Bech and Monnet, 2016). If banks have a liquidity surplus or deficit remaining at the end of the day, they can access the central bank's standing facilities: the deposit facility (DF) and marginal lending facility (MLF).

Banks arrive sequentially, taking into account the trade-off between immediate execution and execution price when deciding whether to post a limit or a market order. Limit orders are valid for one period. The fundamental value of cash, μ_0, is determined by the central bank and is assumed to be fixed. The central bank also determines the range of admissible interest rates $[r_{DF}, r_{MLF}]$ by demanding and supplying an infinite amount of cash at r_{DF} and r_{MLF}, respectively. When entering the market, banks either have a funding surplus or funding deficit. Banks with a funding surplus have a low private valuation for cash ($v_i = -v$) and banks with a funding deficit have a high private valuation for cash ($v_i = +v$). For simplicity, we assume that 50% of banks have a funding surplus and 50% have a deficit. Any other distribution can be easily implemented into the model.

We consider two sets of risk-neutral banks. A proportion θ of banks is exposed to shocks

[6] In Europe, the majority of short-term funding is obtained through the European interbank repo market, which is organized as an anonymous, electronic limit order book market (e.g., Mancini, Ranaldo, and Wrampelmeyer, 2016). In the U.S., limit order books play an important role in the GCF repo market (e.g., Agueci et al., 2014).

that must be balanced urgently (H banks), whereas $1-\theta$ of banks face shocks that are less time-sensitive (L banks). In order to distinguish between the two types, we introduce the parameter $\tau \in [0,1]$. In particular, $1-\tau$ is the expected probability that a funding constraint becomes binding in the subsequent period. This probability is higher for banks that are exposed to time-sensitive funding shocks. More precisely, the probability of a funding shock to become binding in the next period for a bank with type k is $\mathbb{E}^k[1-\tau] = 1-\tau^k$ with $k \in \{H, L\}$, where $\tau^H < \tau^L$. Consequently, τ is an inverse measure of a bank's demand for immediacy. The further τ is below 1, the higher is the demand for immediate execution. This interpretation is similar to that of Foucault, Pagano, and Röell (2013). They define $1-\tau$ as the probability that the market closes in the next period, which makes it impossible to conduct a trade and, therefore, increases the demand for immediate execution.

Order choice

Bank i trades $q \in \{+1, 0, -1\}$ contracts at rate r and makes the following profit:

$$\pi_i = q(\mu_0 + v_i - r), \tag{1}$$

where $q = 1$ denotes borrowing and $q = -1$ lending. Therefore, quotes stay within the interval $[\mu_0 - v, \mu_0 + v]$, banks of type $v_i = +v$ always submit orders to borrow, and banks of type $v_i = -v$ always submit orders to lend.

Consider a borrower who submits, at time t, a limit order at rate b_t. The expected profit is

$$\mathbb{E}_t\left[\pi_t(b_t)\right] = P_t^k(b_t)\left[\mu_0 + v - b_t\right] + \left(1 - P_t^k(b_t)\right)\left[\mu_0 + v - r_{MLF}\right], \tag{2}$$

where $P_t^k(b_t)$ is the probability that a limit order with rate b_t is executed in time (that is, before a funding constraint becomes binding) if the bank is of type k. With probability $(1 - P_t^k(b_t))$, the order is not executed. In this case, the bank can always resort to the central bank and borrow at r_{MLF}. We define $P_t^k(b_t)$ below.

Using Equation (2), we examine the optimal rate b_t^* that the borrower must submit to the limit order book. Let $\hat{b}_{t+1}^k$ be the minimum bid rate a successor lender of type k is willing to accept using a market order. The strategy of a successor lender with high liquidity risk is to use a market order if $b_t \geq \hat{b}_{t+1}^H$. A successor lender with low liquidity risk uses a market order if $b_t \geq \hat{b}_{t+1}^L$.

Given the above strategies for the successor trader at $t+1$, Table 1 summarizes the execution probabilities of a limit order at rate b_t in t. The probability is zero if $b_t < \hat{b}_{t+1}^H$ because neither lending bank H nor L use a market order at this price. If b_t is greater or equal to $\hat{b}_{t+1}^H$ but smaller than $\hat{b}_{t+1}^L$, the limit order gets executed if the successor bank is H bank (probability $= \theta$) that wants to lend (probability $= \frac{1}{2}$), given that the funding constraint has not become binding yet

(probability = τ^k). If $b_t \geq \hat{b}^L_{t+1}$, both banks H and L take the order and, hence, it is sufficient if the successor is a lender and the constraint has not become binding. Consequently, the execution probability—and thereby the danger of non-execution—is driven by the probability that no matching trader arrives in the subsequent period, the proportion of H banks, and by the probability that the constraint becomes binding in the subsequent period.

Table 1: Execution probabilities

Table 1 presents the execution probabilities for limit orders posted by borrowers.

$P^k_t(b) = 0$	if $b < \hat{b}^H_{t+1}$
$P^k_t(b) = \frac{1}{2}\theta\tau^k$	if $\hat{b}^H_{t+1} \leq b < \hat{b}^L_{t+1}$
$P^k_t(b) = \frac{1}{2}\theta\tau^k + \frac{1}{2}(1-\theta)\tau^k = \frac{1}{2}\tau^k$	if $\hat{b}^L_{t+1} \leq b$

The optimal limit order for the borrower, b^*_t, can only be $\hat{b}^H_{t+1}$ or $\hat{b}^L_{t+1}$ because deviating from these rates leads to non-execution or no improvement in the execution probability. For any $\hat{b}^H_{t+1}$ and $\hat{b}^L_{t+1}$, the expected execution probability is smaller for H borrowers because $\tau^H < \tau^L$. The cut-off rate $\hat{a}^k_t$ that makes a borrower of type k indifferent between using a market or a limit order solves:

$$E_t\left[\pi(b^*_t)\right] = \pi(\hat{a}^k_t) \tag{3}$$

$$P^k_t(b^*_t)\left[\mu_0 + v - b^*_t\right] + \left(1 - P^k_t(b^*_t)\right)\left[\mu_0 + v - r_{MLF}\right] = \mu_0 + v - \hat{a}^k_t, \tag{4}$$

where the left-hand side is the expected profit from posting a limit order at b^*_t. The right-hand side is the profit from using a market order that is executed immediately at $\hat{a}^k_t$. Solving for the cut-off borrowing rate $\hat{a}^k_t$ yields

$$\hat{a}^k_t = P^k_t(b^*_t)\left[b^*_t\right] + \left(1 - P^k_t(b^*)\right)\left[r_{MLF}\right]. \tag{5}$$

Hence, the cut-off borrowing rate is a weighted average of the limit order rate and the outside cost. The weights are determined by the execution probability $P^H_t < P^L_t$. The argument for the lender is analogous. The cut-off rate that makes the lender indifferent between using a market or limit order is

$$\hat{b}^k_t = P^k_t(a^*_t)\left[a^*_t\right] + \left(1 - P^k_t(a^*_t)\right)\left[r_{DF}\right]. \tag{6}$$

Based on the cut-off rates, Proposition 1 shows that banks with high liquidity risk use more market orders than banks with low liquidity risk.

Proposition 1 (Order submission).

(i) Borrowers with high liquidity risk have a higher cut-off rate at which they are willing to use a market order than borrowers with low liquidity risk.

$$\hat{a}_t^H \geq \hat{a}_t^L.$$

(ii) Lenders with high liquidity risk have a lower cut-off rate at which they are willing to use a market order than lenders with low liquidity risk.

$$\hat{b}_t^H \leq \hat{b}_t^L.$$

Proof. The results of Proposition 1 follow directly from Equations (5) and (6) and the fact that $P_t^H < P_t^L$. □

Funding cost

Next, we derive the equilibrium interest rates to analyze banks' funding cost. The parameters (τ, μ_0, v) are time-invariant and hence banks' strategies do not depend on time because they face the same decision problem in each period. Therefore, we can focus on steady-state equilibria, which implies that

$$\hat{b}_t = \hat{b} \text{ and } \hat{a}_t = \hat{a} \ \forall t. \tag{7}$$

Using Equations (5) to (7), we compute banks' equilibrium bids, offers, and cut-off rates:[7]

$$\hat{a}^H = \frac{2}{2+\tau^H\theta} r_{MLF} + \frac{\tau^H\theta}{2+\tau^H\theta} r_{DF} \tag{8}$$

$$\hat{b}^H = \frac{\tau^H\theta}{2+\tau^H\theta} r_{MLF} + \frac{2}{2+\tau^H\theta} r_{DF} \tag{9}$$

$$\hat{a}^L = \frac{2}{2+\tau^L} r_{MLF} + \frac{\tau^L}{2+\tau^L} r_{DF} \tag{10}$$

$$\hat{b}^L = \frac{\tau^L}{2+\tau^L} r_{MLF} + \frac{2}{2+\tau^L} r_{DF}. \tag{11}$$

Table 2 summarizes the order submission strategies of high- and low-liquidity-risk banks for all relevant scenarios. The first two columns present the type of bank that is arriving to the market and the state of the order book at the time of arrival. Column three highlights the preferred order type and column four depicts the rates between which the bank is indifferent. For example, borrower H—who arrives in the market when there is an ask quote at $\hat{a}^H$—is indifferent between a market order at $\hat{a}^H$ or posting a limit order at $\hat{b}^H$ or $\hat{b}^L$.

[7] Derivations can be found in the Supplemental Appendix in Part III.

Table 2: Order submission strategy of high and low liquidity risk banks

Table 2 summarizes the order submission strategies of high- and low-liquidity-risk banks for all relevant scenarios. The first two columns show the type of bank that is arriving to the market and the state of the order book at the time of arrival. The third column highlights the preferred order type and the fourth column depicts the rates between which the bank is indifferent.

Arriving bank	State of order book	Order type	Interest rate
H borrower	$\hat{a}^H$	Indifferent	$\hat{a}^H$, $\hat{b}^H$ or $\hat{b}^L$
	$\hat{a}^L$	Market order	$\hat{a}^L$
H lender	$\hat{b}^H$	Indifferent	$\hat{b}^H$, $\hat{a}^H$ or $\hat{a}^L$
	$\hat{b}^L$	Market order	$\hat{b}^L$
L borrower	$\hat{a}^H$	Limit order	$\hat{b}^H$ or $\hat{b}^L$
	$\hat{a}^L$	Indifferent	$\hat{a}^L$, $\hat{b}^H$ or $\hat{b}^L$
L lender	$\hat{b}^H$	Limit order	$\hat{a}^H$ or $\hat{a}^L$
	$\hat{b}^L$	Indifferent	$\hat{b}^L$, $\hat{a}^H$ or $\hat{a}^L$

Comparing the preferred order types for banks H and L, Table 2 indicates that banks with high liquidity risk use more market orders than their low-risk peers. For all four states of the order book, the interest rates paid (received) by high-liquidity-risk borrowers (lenders) are larger (smaller) or equal to the interest rates paid (received) by low liquidity risk borrowers (lenders). We summarize this finding in Proposition 2.

Proposition 2 (**Funding cost**)**.**
In equilibrium, banks with high liquidity risk

(i) pay higher interest rates when borrowing and

(ii) receive lower interest rates when lending

than banks with low liquidity risk.

Proof. The results of Proposition 2 follow directly from Equations (8) to (11) and Table 2. □

The difference in interest rates paid/received by high- and low-liquidity-risk banks depends on the expected bid/ask spread. From Equations (8) to (11), we obtain three possible bid/ask spreads, depending on the sequence with which banks arrive in the market:

$$\hat{a}^H - \hat{b}^H = \frac{4 - \tau^L\tau^H\theta + 2(\tau^L - \tau^H\theta)}{(2+\tau^L)(2+\tau^H\theta)}(r_{MLF} - r_{DF}) \quad \text{with probability } \theta^2 \tag{12}$$

$$\hat{a}^H - \hat{b}^L = \frac{4 - \tau^L\tau^H\theta}{(2+\tau^L)(2+\tau^H\theta)}(r_{MLF} - r_{DF}) = \hat{a}^L - \hat{b}^H \quad \text{with probability } 2(\theta - \theta^2) \tag{13}$$

$$\hat{a}^L - \hat{b}^L = \frac{4 - \tau^L\tau^H\theta - 2(\tau^L - \tau^H\theta)}{(2+\tau^L)(2+\tau^H\theta)}(r_{MLF} - r_{DF}) \quad \text{with probability } (1-\theta)^2. \tag{14}$$

The higher the proportion of high-liquidity-risk banks, θ, the greater the expected bid/ask spread and, hence, the greater the heterogeneity in funding costs.

4. Empirical analysis

The goal of our empirical analysis is to provide evidence for the funding liquidity risk channel and to quantify the markup that borrowers are willing to pay due to their funding liquidity risk. We face three main identification challenges: First, we must isolate funding transactions from transactions with other intentions, such as market making, speculation, arbitrage, or sourcing a specific security. Second, we must construct a proxy for the idiosyncratic funding liquidity risk of borrowers because it is not directly observable. Finally, we must isolate the markup a borrower is willing to pay due to its liquidity risk from the premia required by lenders. We overcome these challenges by exploiting the institutional design of an important segment of the European short-term funding market: the General Collateral (GC) repo market.[8]

4.1 Data and the repo market

We use data from Eurex Repo AG, a major trading platform in the European interbank repo market. In this market, a CCP is at the center of each transaction, functioning as a borrower to every lender and a lender to every borrower. The CCP is responsible for risk management and determines haircuts centrally for all market participants. Repos are traded anonymously via a transparent electronic order book.

We focus on overnight (ON) repos with collateral from the GC Pooling ECB basket to ensure that neither differences in term nor collateral risk can impact our results.[9] In a GC repo, borrowers are free to supply any security included in a predefined basket as collateral. The GC Pooling ECB basket, is one of the major GC baskets in Europe. It includes approximately 3,000 securities that are eligible for open market operations at the ECB and have been rated at least A/A3. The addendum "Pooling" reflects the internationality of the basket. Compared to common GC baskets, which normally cover only one country, the GC Pooling ECB basket includes bonds from Austria, Belgium, France, Germany, Slovenia, the Netherlands, and international Eurobonds (XS ISINs). The bond issuer must be established in the European Economic Area (EEA) or in one of the non-EEA G10 countries (that is, the U.S., Canada, Japan, or Switzerland).

Our data set includes transactions from January 2006 to December 2016, covering 2,807 trading days. It covers 95 banks from over 10 countries that conduct 95,462 trades, amounting to a total volume of EUR 23 trillion. For each trade, the following information is available: time of the trade, collateral basket, trade volume, repo rate, and an anonymous bank ID of

[8] See Mancini, Ranaldo, and Wrampelmeyer (2016) and Nyborg (2016) for a detailed discussion on the market structure of the European interbank repo market.

[9] For instance, Bartolini et al. (2011) show that repo rates secured by Treasury securities trade $6-7$ basis points lower than those secured by agency securities or MBS.

the borrower and lender. We match the repo data with annual bank balance sheet information from SNL Financial using the matching from di Filippo, Ranaldo, and Wrampelmeyer (2020).

The daily repo trading volume averages approximately EUR 27 billion without double counting of lending and borrowing. GC Pooling repos account for 44% of the CCP GC repo market, 29% of the total GC market, and 88% of the total unsecured interbank market.[10] ON repos account for more than 42% of the total turnover at Eurex between 2006 and 2016.[11] The volume of overnight repos follows the same trend as the overall volume. Figure 3 shows aggregate market developments in repo rates and volumes during our sample period.

Panel (a) of Table 3 presents summary statistics for the repo market activity of individual banks. We measure the relative funding costs of banks through their excess rates, which we compute as the volume-weighted average repo rate paid by bank i on day t, $r_{i,t}$, minus the daily volume-weighted average of all overnight transactions from the GC Pooling ECB basket, $\bar{r}_t$:

$$r^e_{i,t} = r_{i,t} - \bar{r}_t. \tag{15}$$

On average, banks borrow EUR 617 million per day, split into 2.56 trades. We define a bank's experience as the cumulative number of trading days, that is, when a bank trades for the first time, this variable takes the value 1; on the second trading day, it takes the value 2, and so on. Panel (b) of Table 3 indicates that our sample covers banks ranging from a balance sheet size of EUR 1 billion to EUR 3,544 billion, with different levels of profitability, leverage, balance sheet structures, and credit risk.

Banks with high funding costs have lower trading volumes and are less experienced than their peers. Interestingly, they are also smaller in terms of their total assets. Banks with high funding costs have higher CDS spreads indicating that funding liquidity risk and credit risk are correlated and, hence, controlling for credit risk in our regression analysis is important.

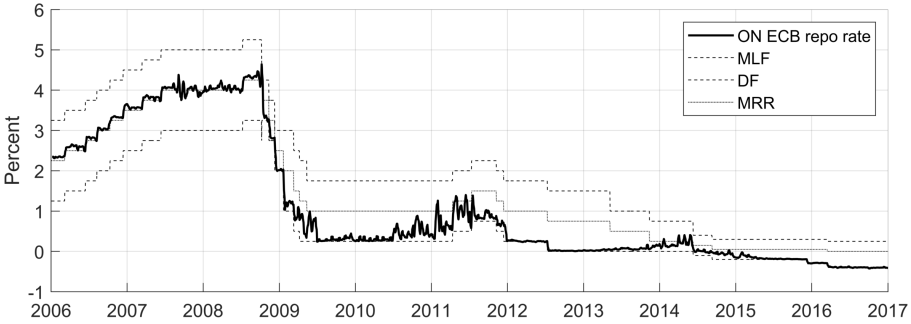
The GC Pooling repo market has unique characteristics that help us address our identification challenges. The CCP-based structure with anonymous trading via an electronic trading platform rules out various potential drivers of interest rates. For instance, asymmetric information, trading relationships, and search costs have been shown to be important drivers of interest

[10]The quarterly cumulative turnover of the secured (repo) and unsecured money market in 2015 is approximately EUR 28 trillion and EUR 2.8 trillion, respectively. The share of GC repos is approximately 30%, of which 66% are centrally cleared through a CCP, 26% are bilateral, and 8% are tri-party repos (European Central Bank, 2015; European Money Market Institute, 2017).

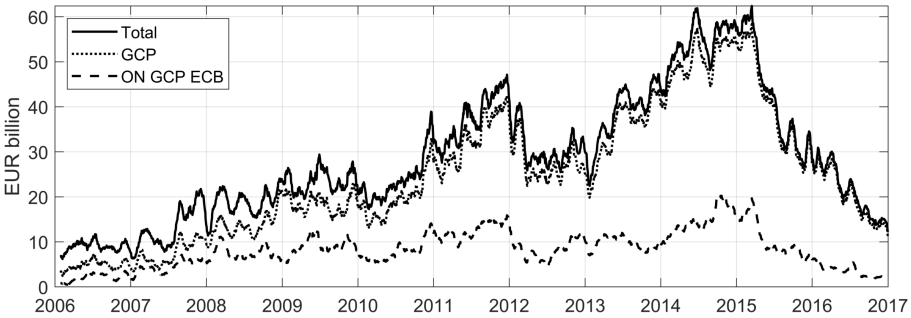
[11]We also analyze repos with tomorrow-next (TN) and spot-next (SN) tenors as a robustness check in Section 4.4. Together with ON repos, these products account for more than 86% of the overall trading volume. ON, TN, and SN are all one-day repos that differ in terms of their purchase and repurchase dates. An ON repo runs from today (t) to tomorrow ($t+1$), TN from $t+1$ to $t+2$, and SN from $t+2$ to $t+3$.

Figure 3: ECB policy rates, repo rates, and repo market volume

Panel (a) of Figure 3 shows the ECB interest rate corridor. The deposit facility (DF) and marginal lending facility (MLF) form the floor and ceiling of the corridor with the main refinancing rate (MRR) in between. The solid black line depicts the rate on ON repos with collateral from the GC Pooling ECB basket. Panel (b) shows the total repo volume at Eurex Repo (solid line), the total GC Pooling repo volume (dotted line), and the ON repo volume with collateral from the GC Pooling ECB basket (dashed line).



(a) ECB interest rate corridor and ON ECB repo rate



(b) Repo volume

rates in unsecured and non-anonymous fixed-income markets (e.g., Ashcraft and Duffie, 2007; Temizsoy, Iori, and Montes-Rojas, 2015; Craig, Fecht, and Tümer-Alkan, 2015), but cannot impact interest rates in the CCP-based European repo market. Due to the fact that haircuts are determined by the CCP and are the same across all market participants, repo rates are not blurred by heterogeneity in haircuts and, thus, they fully capture differences in banks' (repo) funding costs. In the following three subsection, we discuss in more detail how we utilize the market structure to overcome our three identification challenges.

Table 3: Summary statistics

Table 3 presents summary statistics for the daily repo data and the yearly balance sheet data. NT is the number of bank-day observations and N is the number of banks. Balance sheet data is not available for all banks. Trade time is the time of the day in decimals. For example, 13.5 means 1.30 pm. The number of bank-day observations is higher for Experience because we assume any repo trade (not only ON repos from the ECB basket) to increase the experience of a bank.

Panel (a): Repo panel data (daily)

	Mean	Median	Std	Min	Max	NT	N
Excess rate (bp)	−0.05	0.04	2.96	−69.07	75.41	37,346	95
Excess rate (rel. frequency)	0.53	0.59	0.45	0.00	1.00	37,346	95
Market order share	0.53	0.59	0.45	0.00	1.00	37,346	95
Volume	617	320	817	1	12,425	37,346	95
Trade time	12.38	12.28	2.33	5.91	17.00	37,346	95
Number of trades	2.56	2.00	2.43	1	42	37,346	95
Experience	699	554	566	1	2,703	90,955	95

Panel (b): Balance sheet panel data (yearly)

	Mean	Median	Std	Min	Max	NT	N
Total assets (EURbn)	329	87	583	1	3,544	590	63
ROAA	0.20	0.21	0.65	−6.44	3.15	560	63
Leverage	6.13	4.31	6.21	0.00	40.51	538	58
Short/total funding	0.66	0.69	0.25	0.04	1.00	421	41
Short/long funding	54	2	556	0	8,535	421	41
Non-liquid/total assets	0.55	0.57	0.21	0.02	1.00	425	47
CDS	136	115	110	1	679	216	25

4.2 Funding-driven market

In order to address our first identification challenge—that is, isolating funding transactions—we utilize the fact that the GC repo market is a funding market. In a repo based on the GC Pooling ECB basket, borrowers are free to supply any of the 3,000 securities as collateral. Ex ante, lenders do not have knowledge of the exact security they will receive and, hence, they cannot use this market to source a specific asset. Therefore, the GC repo market is widely recognized as funding market that is driven by the demand and supply of cash.[12] Consequently, restricting our analysis to repos from the GC Pooling ECB basket ensures that we exclusively consider funding trades.

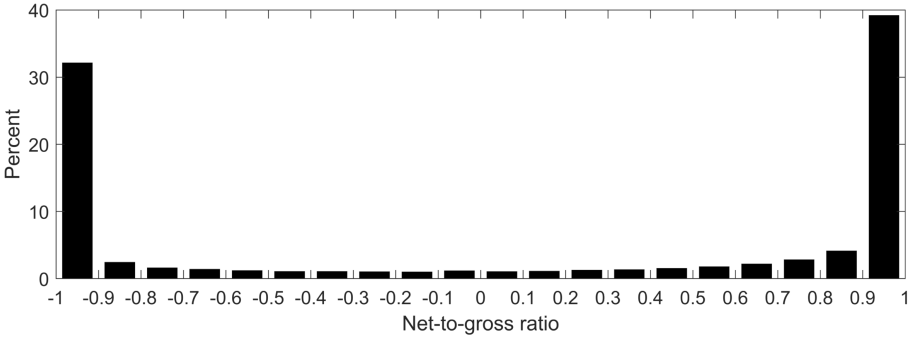
Figure 4 presents additional evidence that GC Pooling repo trading is driven by the need for funding. It plots the distribution of banks' daily net-to-gross ratios, defined as net borrowing over total borrowing and lending. A ratio of 1 indicates that a bank only borrows on a given

[12]There is also a special collateral repo market. In this market, the borrower and lender agree to use a specific asset as collateral. Therefore, special collateral repos are security-driven and rates are determined by the demand and supply of securities instead of cash.

day. Correspondingly, a ratio of −1 indicates pure lending. Banks are (almost) exclusively on one side of the market on a given day, meaning they either only borrow or only lend. This confirms that the GC Pooling repo market is a funding market, where banks balance their in- and outflows of liquidity. Alternative trading strategies, such as market making, speculation, or (cross-basket) arbitrage, would require banks to be equally active on both sides of the market (e.g., Agueci et al., 2014). Additionally, we find that those banks which are on both sides of the market on a given day on average do not make a profit from their trading.

Figure 4: Daily net-to-gross ratios

Figure 4 shows the distribution of daily net-to-gross ratios. The net-to-gross ratio is defined as net borrowing (that is, borrowing − lending) over total borrowing and lending (that is, borrowing + lending). A net-to-gross ratio of 1 indicates that a bank only borrows on a given day. Correspondingly, a ratio of −1 indicates pure lending. The figure includes trades from all GC baskets and tenors at Eurex. Hence, it captures trading across baskets and tenors.



4.3 Measuring idiosyncratic funding liquidity risk

In order to address the second identification challenge—that is, how to measure liquidity risk—we utilize the limit order book structure of the GC repo market. As illustrated in Section 3, banks' demand for immediate execution in the interbank market is a function of their liquidity risk. In limit order books, the demand for immediate execution is observable, meaning that we can measure banks' demand for immediate funding via their order choice. More precisely, banks with high liquidity risk demand immediacy and thus prefer market orders to lock in their funding. Against this background, we derive our proxy for idiosyncratic liquidity risk from banks' volume-weighted shares of market orders. We can do this because the particular market design of the European repo market rules out various other reasons why banks might want to use market orders. For instance, as shown in the previous section, market making does not play a role. The repo market is a funding market, such that a segmentation of participants into noise traders and informed traders known from equity markets does not apply. We control for the

few remaining determinants of order choice that may play a role in the euro GC repo market when constructing the measure below.

Constructing the measure

In Section 3, we provide some preliminary empirical evidence for the link between funding liquidity risk and demand for immediacy, using banks' share of short-term wholesale funding as a proxy for funding liquidity risk. The disadvantage of this proxy is that it is not very accurate and only available at a yearly frequency and for a subset of our banks. In order to get daily variation in funding liquidity risk at the individual bank level, we exploit variation in the daily volume-weighted market order share of banks. To make our measure more precise, we only use the variation in the market order share that is orthogonal to other potential determinants of banks' order choice. More precisely, we use the residuals from the following regression model as our proxy for idiosyncratic funding liquidity risk:

$$MOS_{i,t} = \alpha + X_{i,t}\gamma + \varepsilon_{i,t}, \tag{16}$$

where $MOS_{i,t}$ is the volume-weighted market order share of bank i on day t and $\varepsilon_{i,t}$ is the error term. $X_{i,t}$ is a matrix of potential determinants of banks' order choice that are unrelated to funding liquidity risk.[13] The matrix includes both trade-level determinants as well as common bank-level controls: banks' logged repo volume in EUR million ($Volume$), trade time ($TradeTime$), logged cumulative number of trading days ($Experience$), logged size of total assets in EUR billion ($TotalAssets$), return on average assets ($ROAA$), debt-to-equity ratio ($Leverage$), and logged CDS spreads (CDS).[14]

We include CDS spreads to avoid that our liquidity risk measure is confounded by credit risk. As discussed in Section 4.1, the CCP-based anonymous market design controls for any direct impact of credit risk. However, there might be an indirect channel that links credit risk to banks' order choice in the repo market. Banks with high credit risk might have more difficulties to get funding outside the repo market (for example, in the unsecured market) and hence they are forced to act more aggressively in the repo market to lock in their funding. Against this background, we decided to include CDS spreads in our baseline specification. Balance sheet data

[13]Note that $TradeTime$ might also eliminate some of the variation in liquidity risk to the extent that it captures the time of arrival of banks in the market. The later a bank arrives, the more time-sensitive a funding shock could be, as markets tend to be closing soon. However, $TradeTime$ only measures the execution time of a trade. In particular in the case of limit orders, the execution time of a trade can be far away from the market arrival of a bank. In the Internet Appendix, we run one specification without $TradeTime$. The results remain almost unchanged.

[14]For more information on these variables, see Table A.1 in the Appendix.

and CDS spreads are not available for all banks, thereby reducing the number of observations. In the Internet Appendix, we discuss this in more detail and show that our results are robust to changing the composition of control variables, such as leaving out CDS spreads or adding bank and time fixed effects.[15]

Panel (a) of Table 4 presents summary statistics for our measure, which we call *LiquidityRisk*. Being a residual, it is centered around zero by design. The second and third rows present the summary statistics of *LiquidityRisk* for banks with high and low funding costs, respectively. In line with the funding liquidity risk channel, banks with higher funding costs also have higher funding liquidity risk. Before testing this relationship more thoroughly, we provide additional evidence for the validity of our measure.

Table 4: Summary statistics of *LiquidityRisk*

Table 4 presents summary statistics for *LiquidityRisk*, our measure for banks' idiosyncratic funding liquidity risk. The first row captures the full sample. The second and third rows examine the statistics for banks with high and low funding costs. Banks with high (low) funding costs are defined as having a positive (negative) average excess rate over the full sample. In the fourth and fifth row, we link *LiquidityRisk* to the balance sheet proxy for funding liquidity risk, which we have used in Figure 2 in Section 3.1: the share of short-term wholesale funding of banks.

Panel (a): Repo panel data (daily)

LiquidityRisk	Mean	Median	Std	Min	Max	*NT*
Total	0.00	−0.03	0.42	−0.87	0.88	11,486
High funding costs	0.06	0.14	0.42	−0.87	0.88	6,933
Low funding costs	−0.09	−0.26	0.40	−0.76	0.83	4,553

Panel (b): Balance sheet panel data (yearly)

LiquidityRisk	Mean	Median	Std	Min	Max	*NT*
High share ST wholesale	0.03	0.09	0.27	−0.74	0.46	118
Low share ST wholesale	−0.01	0.02	0.24	−0.74	0.41	118
High share ST deposits	0.11	0.12	0.22	−0.52	0.46	46
Low share ST deposits	0.01	−0.04	0.26	−0.66	0.39	46

Testing the validity of the liquidity risk measure

To support the validity of our proxy, we examine its relationship to alternative measures of funding liquidity risk. We begin by examining conventional measures that are derived from balance sheet data, such as the share of short-term wholesale funding of banks, which we have

[15] In Section 5, we provide additional evidence that our measure is not confounded by credit risk or other omitted variables.

already used as a proxy for funding liquidity risk in Figure 2 in Section 3.1. Additionally, we compute the fraction of demand deposits—which are redeemable without prior notice—over total deposits. Panel (b) of Table 4 presents the summary statistics of *LiquidityRisk* for banks with high and low funding liquidity risk as indicated by these balance sheet measures. As expected, *LiquidityRisk* is higher for banks that rely heavily on short-term wholesale or deposit funding.

In our second validity test, we examine if *LiquidityRisk* captures increased liquidity risk that originates from liquidity shocks. This is a direct test of the funding liquidity risk channel, which posits that liquidity risk originates from the exposure to liquidity shocks. We identify liquidity shocks as a change in the direction of trading from lending to borrowing. In the previous section, we have shown that banks enter the GC Pooling market first and foremost to manage their funding; in particular, market making, speculation, and arbitrage strategies are negligible. Therefore, market participants are usually only on one side of the market, implying that they either only borrow or only lend on a given day. When a bank enters the market as a lender and subsequently during the day switches to borrowing, this is most likely caused by a negative liquidity shock that forces the bank to correct its funding position.

Table 5 presents the results of a logistic regression evaluating if our measure for liquidity risk captures the risk originating from liquidity shocks. The dependent variable is a binary variable that becomes 1 if *LiquidityRisk* is positive. The independent variable, *Switch*, is also a binary variable. It takes the value 1 on days when a bank enters the market as lender and later switches to borrowing. Hence, *Switch* indicates if banks are exposed to a liquidity shock on a given day. The odds of having a positive liquidity risk more than double in the presence of a liquidity shock.[16] Note that according to the funding liquidity risk channel, a liquidity shock should only lead to high funding pressure if it is time-sensitive, that is, if the bank needs the liquidity immediately. In contrast to our measure of funding liquidity risk, *Switch* does not capture the time-sensitivity of liquidity shocks. Therefore, in our third validity test, we exploit a setting where the time-sensitivity of shocks is observable.

The third validity test examines banks' *LiquidityRisk* at the end of the ECB's maintenance periods. In order to fulfill the ECB's reserve requirements, banks need to hold a certain average amount of liquidity over the reserve maintenance period. If banks have not yet fulfilled these requirement toward the end of the period, they are obliged to acquire the missing reserves to avoid fines.[17] Consequently, liquidity shocks at the end of the maintenance period are more likely to be time-sensitive and, hence, we expect our measure for liquidity risk to be higher for

[16] In the Internet Appendix, we present a contingency matrix showing the joint frequency distribution of *LiquidityRisk* and *Switch*.

[17] In contrast to the Federal Reserve, the ECB does not allow banks to carry over any reserve deficits/surpluses into the following reserve maintenance period.

Table 5: Validity test of *LiquidityRisk*: Logistic regression

Table 5 presents the results of a logistic regression of $LiquidityRisk > 0$ on *Switch*. The former is a binary variable that becomes 1 when *LiquidityRisk* is positive. *Switch* is a dummy that takes the value 1 on days when a bank enters the market as lender and later switches to borrowing. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	$LiquidityRisk > 0$	Odds Ratio
Switch	0.820^{***}	2.271^{***}
	(11.53)	(11.53)
Constant	-0.248^{***}	
	(-23.72)	
N	38,003	38,003

those days.

In Table 6, we focus on the last three days of the maintenance period t, $t-1$, and $t-2$. After being hit by a liquidity shock on these days, banks have three possibilities of obtaining funding to fulfill the reserve requirement: (1) They can conduct an ON repo at t, (2) a TN repo at $t-1$, (3) or a SN repo at $t-2$. All three strategies guarantee funding on the last day of the maintenance period.[18] Table 6 presents the *LiquidityRisk* in excess of the maintenance period average for banks trading ON, TN, and SN repos. The columns depict the last three days of the maintenance period. The numbers in bold identify the repo contracts that provide funding on the last day of the maintenance period. For instance, one day before the end of the maintenance period ($t-1$), conducting a TN repo enables banks to lock in funding on the last day of the period. In line with our expectations, *LiquidityRisk* is significantly greater for those contracts that lock in liquidity on the last day of the maintenance period.

Table 6: Validity test of *LiquidityRisk*: End-of-maintenance period

Table 6 summarizes the differences in liquidity risk of borrowers at the end of the maintenance period compared to all other days of the period. t indicates the last day of the maintenance period, $t-1$ and $t-2$ the two preceeding days. The numbers in bold are repo contracts that provide funding on the last day of the maintenance period. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	t	$t-1$	$t-2$
ON	$\mathbf{0.033}^{***}$	-0.023^{***}	-0.041^{***}
TN	0.032^{**}	$\mathbf{0.123}^{***}$	-0.001
SN	0.004	0.063^{***}	$\mathbf{0.112}^{***}$

[18] Recall, that ON repos run from today (t) to tomorrow ($t+1$), TN from $t+1$ to $t+2$, and SN from $t+2$ to $t+3$.

4.4 Quantifying the funding liquidity risk markup

In this section, we quantify the effect of funding liquidity risk on funding costs, that is, we quantify the markup that borrowers are willing to pay to lock in their funding following a liquidity shock. The market structure of the euro GC repo market also allows us to tackle the third identification challenge, which requires us to decompose repo rates into the markup that borrowers are willing to pay due to their funding liquidity risk and the premium required by lenders as compensation for credit and (market) liquidity risk. Because trading in the market is anonymous and conducted via a CCP, there is no direct exposure between borrowers and lenders and counterparty identities are not revealed. Hence, lenders cannot demand risk premia that are specific to individual borrowers. Therefore, we can be sure that repo rates in the CCP-based GC repo market do not carry any lender premia specific to individual borrowers.

Baseline analysis

Due to the favorable market design of the CCP-based GC repo market, we can run the following regression in order to quantify the borrower markup, which will be measured by the coefficient β:

$$r^e_{i,t} = \beta \; LiquidityRisk_{i,t} + X_{i,t} \; \theta + \eta_i + \lambda_t + \varepsilon_{i,t}, \tag{17}$$

where $r^e_{i,t}$ is the excess repo rate of bank i on day t, $LiquidityRisk_{i,t}$ is our proxy for banks' idiosyncratic funding liquidity risk, $X_{i,t}$ is a matrix of control variables, η_i is a fixed effect for bank i, λ_t is a fixed effect for day t, and $\varepsilon_{i,t}$ is the error term. The matrix of controls is identical to the first stage in Equation (16). It includes banks' logged daily repo volume in EUR million ($Volume$), average trade time ($TradeTime$), logged cumulative number of trading days ($Experience$), logged size of total assets in EUR billion ($TotalAssets$), return on average assets ($ROAA$), debt-to-equity ratio ($Leverage$), and logged CDS spreads (CDS).

Columns (1) to (3) of Table 7 present the regression results of our first and second stage baseline specification. All models are estimated using OLS and robust standard errors that are clustered at the bank-day level. In the first stage (Column (1)), all regressors except for $Volume$ are insignificant. In particular, the coefficient of CDS spreads is insignificant. This is in line with the fact that the market design controls for any direct impact of credit risk. It also suggests that credit risk does not have any indirect impact on funding costs.

In the two specifications of the second stage regression in Columns (2) and (3), the coefficient of $LiquidityRisk$ is positive and statistically significant, ranging between 1.6 and 2.0. Consequently, borrowers with high liquidity risk pay up to 2 basis points more on a given day than their low-risk peers. In light of the large daily transaction volumes in interbank funding markets—on average, banks borrow EUR 617 million per day—these results are not only statistically significant but also economically meaningful. A one standard deviation increase in

liquidity risk increases the nominal costs of short-term funding by over 2.5%. Funding liquidity risk has a similar magnitude as the impact of credit risk in unsecured markets, as documented by Angelini, Nobili, and Picillo (2011). In their paper, a downgrade in a bank's Fitch individual rating from A (best) to C (middle of the range) corresponds to an increase in rates spreads of 0 to 5 basis points depending on the sample and econometric specification. In addition, it stands to reason that we only measure the lower bound of the effect because the CCP-based GC repo market is one of the most liquid and sophisticated segments of the euro funding market. Moreover, the maximum effect is capped by the bid-ask spread. Even if a bank is willing to pay higher rates, it can always accept the best existing limit order from the order book. This creates a cap for its maximum cost and biases our results downward. Hence, in markets without a limit order book, it seems likely that the effect has an even larger magnitude.

$TradeTime$ is the only control variable that has a statistically and economically significant effect on funding costs. Trades that are executed later in the day decrease funding costs by approximately 0.3 basis points per hour. This effect is known as intraday interest rate and has been analyzed by, among others, Furfine (2001), Baglioni and Monticini (2008), and Abbassi, Fecht, and Tischer (2017), who find a similar magnitude for the intraday rate. It is important to note that decreasing repo rates during the day are not in opposition to the funding liquidity risk channel. The channel does not make predictions regarding the level of interest rates. Instead, it provides an explanation for the cross-sectional distribution around the average market rate.

Funding liquidity risk markup in different subperiods

In this section, we investigate how the relationship between liquidity risk and funding costs changes across two major subsamples of the data: the financial crisis and the floor system. The former is defined as the time between July 2007 and July 2009 and is characterized by high levels of volatility, uncertainty, and illiquidity in financial markets. The floor system refers to the time after the allotment of the two major long-term refinancing operations (LTROs) of the ECB around the beginning of 2012. It also includes European Quantitative Easing (QE), which began in March 2015. Both policies produced high levels of excess reserves, driving money market rates to the lower bound of the ECB's interest rate corridor.

Columns (4) and (5) of Table 7 present the regression results. High funding liquidity risk is more costly during crises and less costly in a floor system. The coefficient of $LiquidityRisk$ is close to three times larger in the crisis period. This result is intuitive as it implies that high liquidity risk is more costly when liquidity is scarce. It is also in line with our theory, which shows that a higher proportion of banks with high liquidity risk increases the funding cost differential between high- and low-liquidity risk banks.

Our findings across subperiods highlight a link between funding liquidity risk and market liquidity in funding markets. Banks with high funding liquidity risk have a higher demand for immediacy and are, therefore, willing to pay the bid/ask spread in the funding market. During

Table 7: Liquidity risk and funding costs (panel regression)

Columns (1) to (3) of Table 7 present the results of the baseline two-stage regression analysis with the first stage in Column (1) and the second stage in Columns (2) and (3). Columns (4) and (5) show the results of a subsample analysis for the financial crisis and times of high levels of excess liquidity, which we call floor system. "Financial crisis" is defined as the Global Financial Crisis (1 July 2007 – 31 July 2009). "Floor system" is defined as the time after the allotment of the two major LTROs around the beginning of 2012 (1 January 2012 – 31 Dec 2016). It also includes the ECB's Quantitative Easing. Funding costs are measured by the daily excess repo rate in basis points. *LiquidityRisk* is our proxy for the idiosyncratic funding liquidity risk of banks, as presented in Section 4.3. All models are estimated via least square dummy variable (LSDV) regressions, including bank and day fixed effects. *Experience* is measured by the cumulative number of trading days in logs. $Volume$, $TotalAssets$, and CDS spreads are also in logs. t-statistics are shown in parentheses. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	Baseline			Crisis	Floor
	(1)	(2)	(3)	(4)	(5)
	MOS	r^e	r^e	r^e	r^e
LiquidityRisk		1.915***	2.005***	2.712***	1.005***
		(9.22)	(10.62)	(9.85)	(7.69)
Volume	−0.0641***		0.124*	0.675***	−0.0490
	(−6.56)		(1.79)	(5.22)	(−0.98)
TradeTime	−0.0102		−0.327***	−0.433***	−0.0377
	(−1.02)		(−9.50)	(−3.28)	(−1.33)
Experience	0.0292		−0.0683	−0.702	0.0358
	(1.66)		(−0.36)	(−1.49)	(0.32)
TotalAssets	0.0495		1.493	−0.0265	0.0978
	(1.36)		(1.42)	(−0.03)	(0.10)
ROAA	−0.0324		0.158	0.0287	0.426
	(−0.95)		(1.21)	(0.16)	(1.52)
Leverage	−0.00415		0.0182	0.00286	0.00844
	(−1.34)		(0.75)	(0.15)	(0.14)
CDS	0.0172		0.00631	−0.222	0.331
	(0.95)		(0.11)	(−1.28)	(1.39)
Constant	0.455*	-0.184***	−5.590	5.291	−1.926
	(1.93)	(-158.30)	(−0.89)	(0.86)	(−0.35)
Bank/Day FE	no/no	yes/yes	yes/yes	yes/yes	yes/yes
NT	11,486	11,486	11,486	2,207	4,591
R^2	0.0600	0.236	0.267	0.288	0.432
Adj. R^2	0.0594	0.0368	0.0758	0.0576	0.275

crises, market liquidity in the funding market is low and hence bid/ask spreads are high. In a floor system, funding markets are liquid due to the excess liquidity and, hence, bid/ask spreads are low. Consequently, having high idiosyncratic funding liquidity risk is particularly costly

when market liquidity in funding markets is low. This finding complements the extant literature that links asset market liquidity and funding illiquidity (e.g., Brunnermeier and Pedersen, 2009).

Robustness checks

In this section, we provide additional analyses to support the robustness of our empirical findings. We show that the size of the funding liquidity risk markup is robust to different econometric specifications, that it is not driven by extreme observations, and that it is similar across different tenors and collateral baskets.

Dynamic panel model. In light of the persistence in funding costs, we extend our main regression model to allow for autocorrelation of the dependent variable by adding its first lag to the model:

$$r^e_{i,t} = \rho\ r^e_{i,t-1} + \beta\ LiquidityRisk_{i,t} + X_{i,t}\ \theta + \eta_i + \varepsilon_{i,t}. \tag{18}$$

We estimate this model using the two-step Arellano and Bond (1991) dynamic panel estimator. Panel estimators usually control for unobserved heterogeneity by first-differencing. Since our data is unbalanced, we instead apply forward orthogonal deviations as in Arellano and Bover (1995). In order to keep the number of instruments small and avoid instrument proliferation, we exclude the time fixed effects and restrict lags for the GMM moment conditions to five.[19]

Column (1) of Table 8 present the results. Similar to our main results, the coefficient of *LiquidityRisk* is positive and significant. The tests for first- and second-order autocorrelation indicate that our model is well specified using the first lag of the dependent variable.

Relative frequencies. To eliminate the possibility that our results are driven by outliers in the excess rate, $r^e_{i,t}$, we employ the relative frequency of having a positive excess rate, $RF_{i,t}$, as an alternative measure for banks' funding costs:

$$RF_{i,t} = \frac{\sum_{q=1}^{Q_{i,t}} \mathbb{1}(r^e_{i,t,q} > 0)}{Q_{i,t}}, \tag{19}$$

where $\mathbb{1}$ is the indicator function, $r^e_{i,t,q}$ is bank i's excess rate from its q-th trade on day t, and $Q_{i,t}$ denotes the total number of trades for each bank and day. A relative frequency of 0.5 implies that bank i pays more than the daily volume-weighted average repo rate in 50% of its trades. While $r^e_{i,t}$ is the more direct measure, $RF_{i,t}$ is robust to outliers because it is between 0 and 1 by construction.

Figure 5 replicates Panel (a) of Figure 1 using relative frequencies instead of excess rates.

[19] Control variables enter with their first lag and beyond, which is equivalent to treating them as predetermined. The results remain numerically similar and qualitatively equivalent when all variables are entered beginning with their second lag and, hence, treating everything as endogenous.

Table 8: Robustness checks

Table 8 presents the results of our robustness checks. In Column (1), we employ the two-step Arellano-Bond dynamic panel estimator with Windmeijer error corrections. All explanatory variables are instrumented by their first lag. To keep the total number of instruments small, the GMM moment conditions are limited to five lags lags. In Column (2), we use the relative frequency of having a positive excess rate, RF, as dependent variable. Columns (3) and (4) replicate the regression results of our main model using tomorrow-next (TN) and spot-next (SN) repos as well as collateral from the riskier ECB EXTended basket. $LiquidityRisk$ is our proxy for the idiosyncratic funding liquidity risk of banks, as presented in Section 4.3. $Experience$ is measured by the cumulative number of trading days in logs. $Volume$, $TotalAssets$, and CDS spreads are also in logs. t-statistics are shown in parentheses. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	(1)	(2)	(3)	(4)
	r^e	RF	TN/SN	ECB EXT
$LiquidityRisk$	2.245^{***}	0.381^{***}	0.870^{***}	2.054^{***}
	(5.76)	(17.43)	(8.36)	(7.84)
r^e_{t-1}	0.0809^{**}			
	(2.08)			
Constant		-0.305	-1.962	-2.209
		(-0.36)	(-0.56)	(-0.26)
Controls	yes	yes	yes	yes
Bank/Day FE	yes/yes	yes/yes	yes/yes	yes/yes
NT	8,599	11,486	7,720	3,519
Adj. R^2		0.252	-0.0320	0.0990
Instruments	18			
AR(1) p-value	0.00601			
AR(2) p-value	0.966			
Hansen p-value	0.255			

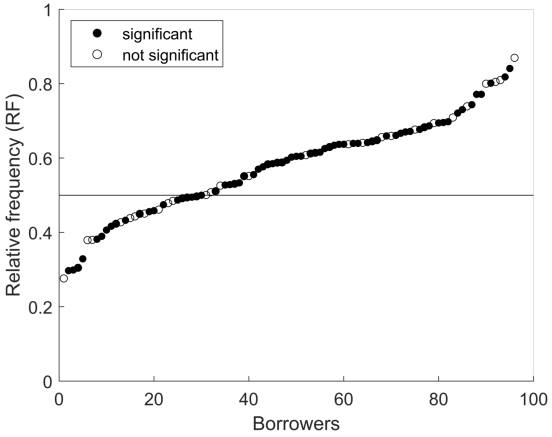
The borrower located at the extreme left has the lowest RF of below 0.3, implying that this bank pays more than the daily average in less than 30% of its trades. The borrower on the right end of the distribution pays more than the daily average in approximately 90% of its trades.

Column (2) of Table 8 presents the regression results of the main regression model using $RF_{i,t}$ instead of $r^e_{i,t}$ as the dependent variable. The results are similar; in particular, $LiquidityRisk$ is positive and significant in all specifications. The likelihood of paying more than average increases by approximately 38% for banks with high liquidity risk.

Different tenors and collateral baskets. As a final robustness check, we repeat our regression analysis using repos with alternative tenors and collateral baskets to support the external validity of our results. We estimate our main regression model (Equation (17)) using TN and SN repos as well as repos with collateral from the riskier GC Pooling ECB EXTended

Figure 5: Heterogeneous funding costs (relative frequencies)

Figure 5 presents for every borrower the relative frequency, RF, of having a positive excess rate. In other words, it shows the proportion of trades in which each borrower pays more than the daily volume-weighted average repo rate. Banks on the x-axis are ordered according to their performance. The filled black circles denote statistical significance at the 5% level. A relative frequency of 0.5 implies that a borrower pays more than average in 50% of its trades. This figure is similar to Panel (a) of Figure 1, but it is robust to outliers because RF is between 0 and 1 by construction.



basket.[20] Columns (3) and (4) of Table 8 present the results. The positive relationship between liquidity risk and funding costs is evident in both specifications. For the ECB EXTended basket, the coefficient of $LiquidityRisk$ has a similar magnitude as in our baseline specification. For TN and SN repos, the magnitude is slightly smaller, which makes sense because time sensitivity should generally be lower for these tenors because a bank can always fall back on an ON repo if it is unable to execute a TN or SN repo. In other words, instead of conducting a TN (SN) repo today, a bank can do an ON repo tomorrow (the day after tomorrow).

5. Omitted variables concerns

The market design of the GC Pooling repo market rules out the most obvious and important confounding variables. However, there might still be concerns about potential omitted variables that bias our results. In this section, we provide further analyses to show that credit risk,

[20]The ECB EXTended basket includes around 14,000 ECB eligible securities with the minimum rating requirement being equal to the one applied by the ECB. Compared with the GC Pooling ECB basket, the list of eligible securities includes riskier securities. More precisely, the location of issuance is extended to Finland, Ireland, Italy, Luxembourg, Malta, and Spain.

preferred habitat, and collateral holdings do not affect our measure and our estimates for the size of the funding liquidity risk markup. Moreover, we implement a one-step estimation approach and apply the methodology of Oster (2019) to bound the effect of potential omitted variables more generally.

5.1 Credit risk

A potential concern about the validity of our measure is that it picks up forms of credit risk that are not captured by a bank's 5-year CDS spread which we include as control variable in our regression analysis. We address this concern in multiple ways. First, rather than controlling for the level of CDS spreads, we include changes in CDS spreads to better capture innovations in credit risk. Second, we repeat our analysis focusing on periods in which credit risk plays a minor role and examine if our results hold. Finally, we exploit the richness of our data set and redo the analysis with lender data as the trading activity of lenders should be unaffected by credit risk.

Innovations in credit risk and subsample analysis

In the first stage of our baseline regression model, we include CDS spreads to make sure that the residual, which ultimately serves as our measure, is free of credit risk. The first stage regression results of our baseline specification can be found in Column (1) of Table 7. The coefficient for the CDS spreads is insignificant, indicating that credit risk does not impact the order choice of banks in the anonymous CCP-based repo market. Hence, already starting point for constructing our liquidity measure, the market order share, seems to be unrelated to credit risk. Consequently, the measure itself will also be unrelated to credit risk.

Table 9 presents two alternative ways of controlling for credit risk. In order to better capture innovations in credit risk, we include CDS spreads in first-differences. If credit risk impacts our measure, it would be particularly strong when there is a shock to banks' credit risk, that is, when CDS rates move strongly. Column (1) of Table 9 shows the first-stage results. The coefficient of ΔCDS is insignificant. This is in line with our baseline results and the fact that credit risk plays no role for the order choice of banks and thus for our measure. Additionally, as shown in Column (2), our coefficient of interest ($LiquidityRisk$) hardly changes compared to the baseline specification. It remains at about 2 basis points.

Ratings are an alternative way of capturing the credit risk of banks. Credit risk should play a dominant role particularly for the behavior of banks around rating changes. To ensure that our measure for liquidity risk is not driven by these rating shocks, we conduct a subsample analysis, dropping all observations two weeks around changes in Standard & Poor's credit ratings of banks. Results presented in Column (2) and (3) of Table 9 are consistent with our baseline results. In particular, the coefficient of interest ($LiquidityRisk$) hardly changes when dropping

observations around rating changes.

Table 9: Omitted variables

Table 9 presents results of three robustness checks that address concerns about credit risk being an omitted variable. Columns (1) and (2) present the first- and second-stage results when using first-differences of CDS spreads to control for credit risk instead of levels. Columns (3) and (4) show results on a subsample analysis where we drop all observations two weeks before and after a change in banks' Standard & Poor's credit ratings. Finally, Columns (5) and (6) present the results of the lender regression. *LiquidityRisk* is our proxy for the idiosyncratic funding liquidity risk of banks, as presented in Section 4.3. *Experience* is measured by the cumulative number of trading days in logs. $Volume$, $TotalAssets$, and CDS spreads are also in logs. t-statistics are shown in parentheses. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	Δ CDS		Subsample		Lender	
	(1)	(2)	(3)	(4)	(5)	(6)
	MOS	r^e	MOS	r^e	MOS	r^e
LiquidityRisk		2.009***		1.970***		−1.851***
		(10.67)		(9.78)		(−7.94)
Δ CDS	-0.0464	0.828				
	(-1.17)	(1.56)				
CDS			0.0191	0.00487	0.0456	0.205
			(1.08)	(0.09)	(1.39)	(1.29)
Constant	0.554*	-5.172	0.490*	-6.400	0.645*	1.920
	(1.80)	(-0.86)	(2.03)	(-1.02)	(2.11)	(0.22)
Controls	yes	yes	yes	yes	yes	yes
Bank/Day FE	no/no	yes/yes	no/no	yes/yes	yes/yes	yes/yes
NT	11,485	11,485	10,418	10,418	4,861	4,861
R^2	0.0587	0.268	0.0606	0.295	0.149	0.414
Adj. R^2	0.0581	0.0763	0.0600	0.0985	0.148	0.106

Lender analysis

In this subsection, we provide additional evidence that our results are not driven by credit risk. To this end, we examine the trading and pricing behavior of banks when lending. The idea behind this test is that the borrowing and lending behavior of banks differs depending on whether it is driven by funding liquidity risk or credit risk. The funding liquidity risk channel predicts that banks with high liquidity risk have a high demand for immediacy (and hence a high market order share) irrespective of whether they borrow or lend. Negative shocks lead to demand for borrowing immediacy and positive shocks lead to demand for lending immediacy. According to the indirect credit risk channel, on the other hand, a high demand for immediacy

should only exist for borrowers.[21] A bank with high credit risk might have a high demand for borrowing immediacy because credit risk impedes the acquisition of liquidity from alternative sources, such as the unsecured funding market. However, there is no reason why banks with high credit risk should have a systematically high demand for lending immediacy. Against this background, we are able to construct a simple test for the presence of the indirect credit risk channel: If credit risk drives our results, we should find significant results only for borrowers. Finding significant results for borrowers *and* lenders would strongly support the funding liquidity risk channel.

Examining the repo market from the perspective of lenders brings about two changes. First, the repo rate is not a cost anymore but a revenue. Second, demand for immediacy is the urgent need to lend instead of the need to borrow. As motivated in Section 3, the funding liquidity risk channel posits that lenders face the same pressure to efficiently manage their liquidity as borrowers. Lenders with a funding surplus can use the repo market to safely invest their excess liquidity. If they fail to do so until the end of the trading day, they must resort to the deposit facility at the ECB.[22] The latter normally pays less and, hence, represents an opportunity cost for repo lenders, just as the marginal lending facility does for borrowers.

Repeating our analysis for lenders reveals that funding liquidity risk is also a major driver of heterogeneity in interest rates when lending. Panel (a) of Figure 6 plots the cross-sectional distribution of average excess rates earned by lenders. Similar to borrowing rates (see, Figure 1), lending rates are heterogeneous. Panel (b) further indicates that the link between funding liquidity risk, the demand for immediacy, and interest rates also exists for lenders. We proxy the funding liquidity risk of lenders by grouping banks into those that have access to the deposit facility of the ECB and those that do not. Banks without access to the central bank have higher funding liquidity risk because they are forced to lend their surplus liquidity in the private market. This becomes problematic especially in times of high levels of excess liquidity, when private money market rates trade close to or even below the deposit facility rate. The black (grey) bars illustrate average market order shares and lending rates of bank-year observations with funding liquidity risk of non-access (access) banks. In line with the funding liquidity risk channel, banks with high funding liquidity risk have a significantly higher demand for lending

[21] Recall, that we control for any direct effects of credit risk via the market design. However, there might be an indirect channel: Borrowers with high credit risk might have more difficulties to get funding outside the repo market (for example, in the unsecured market) and hence they are forced to act more aggressively in the repo market to lock in their funding.

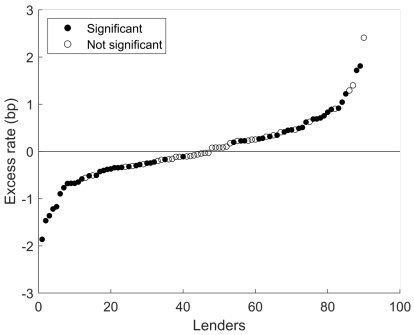
[22] The unsecured money market would be another alternative. However, unlike unsecured borrowing, unsecured lending is conceptually rather different from lending via repos, (credit) risk management considerations come into play. On the other hand, depositing liquidity at the central bank is similar to using CCP repos because it is secured and without credit risk.

immediacy as indicated by their market order share. Simultaneously, these banks also earn significantly less from lending.

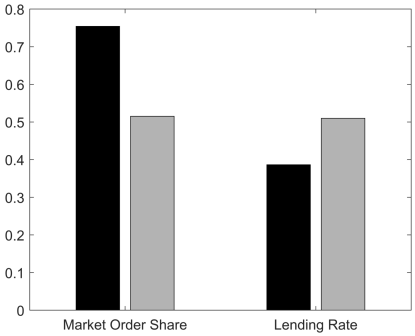
Finally, we also redo the regression analysis for lenders. Columns (5) and (6) of Table 9 show the first- and second stage regression results for lenders.[23] The lender perspective is completely consistent with what we find for borrowers in the sense that revenues are heterogeneous and driven by liquidity risk. This allows us to reject the alternative hypothesis that differences in funding costs arise due to credit risk.

Figure 6: Heterogeneous funding costs and funding liquidity risk channel intuition (lenders)

Panel (a) of Figure 6 presents for each lender the average daily repo rate received in excess of the average volume-weighted market rate. In other words, it shows the average additional return from lending compared to the market average. Banks on the x-axis are ordered according to their performance. The filled black circles denote statistical significance at the 5% level. Panel (b) presents the average market order shares and the return from lending for lenders with high and low funding liquidity risk. The black (grey) bars illustrate average market order shares and returns of bank-year observations of banks without (with) access to the ECB's deposit facility. We measure lending returns as the relative frequency of having a positive excess rate. More precisely, a relative frequency of 0.5 implies that banks receives less than the daily volume-weighted average repo rate in 50% of their trades. In our empirical analysis, we mainly use the excess rate directly as a measure for lending rates. For illustrative purposes, the relative frequency is better suited here because it is between 0 and 1 by construction.



(a) Cross-section of average excess rates



(b) Funding liquidity risk channel intuition (lender)

5.2 Preferred habitat and collateral holdings

Banks might have a preferred habitat for holding cash, specific money market instruments (e.g., Ogden, 1987), certain (HQLA) assets due to regulatory requirements, or they are specialized

[23] We also test the validity of our proxy for the liquidity risk of lenders. In other words, we examine whether the proxy is able to capture increased risk from liquidity shocks to lenders. The results are presented in the Internet Appendix and are similar to the case of borrowers. Hence, our proxy also captures the increase in liquidity risk from liquidity shocks for lenders.

in particular segments of the repo market. If a bank has a preferred habitat or is specialized in a specific segment of the repo market, we would expect this bank to behave differently in this segment than in others. Similarly, if a bank holds assets that are tailored to a certain collateral basket, it might have a higher willingness to pay in this basket, but not in others. Additionally, while specific collateral holdings might incentivize a bank to borrow in a certain basket, they also disincentivise the bank to lend in this basket. In a nutshell, preferred habitat, specialization, and heterogeneous collateral holdings lead to differing behavior of banks across different segments of the repo market.

According to the funding liquidity risk channel, on the other hand, the behavior of banks should not differ across different segments of the repo market. It only depends on their exposure to idiosyncratic liquidity shocks, which is independent of the market segment and independent of whether a bank borrows or lends. The funding liquidity risk channel predicts that the same banks that are willing to pay higher rates when borrowing also accept lower rates when lending, independently of the collateral or the tenor of a repo.

Panel (a) of Figure 7 presents the performance of our banks as measured by their relative frequency of having a positive excess rate, RF, when borrowing or lending. It suggests that banks that perform well (pay less) as borrowers also tend to perform well (receive more) as lenders. In other words, banks with low funding costs when borrowing tend to make high revenues when lending and vice versa. Panel (b) presents the performance of banks when borrowing in the ECB or the riskier ECB EXTended basket. Banks that pay a markup in the ECB basket also tend to pay a markup in the ECB EXTended basket. The figure for the performance of banks across different tenors looks similar and can be found in the Internet Appendix. Overall, these findings are consistent with the funding liquidity risk channel: Some banks are systematically more exposed to funding liquidity risk and, thus, demand more immediacy across borrowing, lending, tenors, and collateral baskets. This increases the funding costs of these banks.

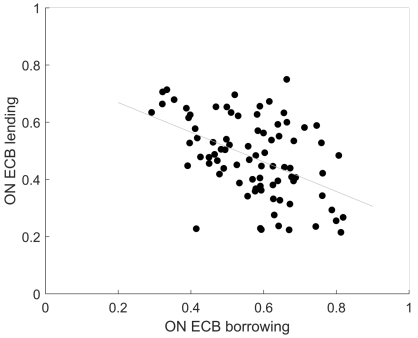
5.3 Bounding the effect of unobservable variables

In this subsection, we use the methodology of Oster (2019) to bound the potential bias in our estimate of the liquidity risk markup arising from unobserved variables not included in our regression. While the previous subsections focus on credit risk, preferred habitat, and collateral holdings, the approach of Oster (2019) allows us to more generally address the concern that the liquidity risk markup might be related to something else than liquidity risk.

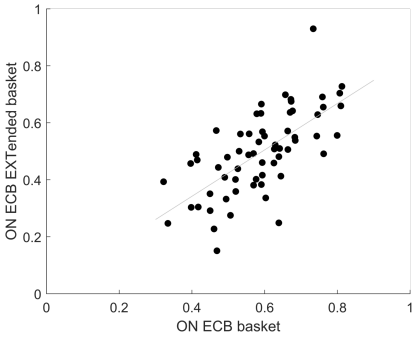
The method is implemented by quantifying the liquidity risk markup in a one-step approach by regressing funding cost on the market order share with and without controls. From the estimated coefficients and R-squares, we can derive bounds on any omitted variable bias by making assumptions about the importance of omitted variables relative to observed variables, δ, and the R-squared from a hypothetical regression of the funding cost on both observed and unobserved controls, R^2_{max}. We follow the recommendations of Oster (2019) and choose

Figure 7: Performance across borrowing, lending, and collateral baskets

Panel (a) of Figure 7 presents the performance of banks across borrowing and lending and Panel (b) across the ECB and the riskier ECB EXTended basket. The relative frequency of banks is used as the performance measure. It ranges from 0 to 1; a value of 0.5 means a bank pays more than the daily average repo rate in 50% of its trades. Every dot represents one bank. Outperforming the market means having a relative frequency greater than 0.5 when borrowing and smaller 0.5 when lending.



(a) Performance across borrowing and lending



(b) Performance across collateral baskets

$\delta = 1$ and $R^2_{max} = 1.3\tilde{R}$, where $\tilde{R}$ is the R^2 from our regression including all controls. These assumptions are conservative as they imply that potential unobserved variables are equally important as observed variables. In fact, it is extremely unlikely that omitted variables explain more than the variables included in the model because (i) the market structure rules out many potential omitted variables and (ii) various (observable) controls motivated by the literature are already included.

Table 10 presents the results. The liquidity risk markup estimated in a one-step regression of funding cost on the share of market orders is 2.0 basis points with controls and 1.4 basis points without any controls. Using these coefficients, the corresponding R-squares and the assumptions about δ and R^2_{max}, we compute the interval for the liquidity risk markup which is shown in Column (3). If there were unobserved variables that are equally important as all the observed variables and fixed effects already included in our model, the borrower markup would still be close to our original estimate of 2 basis points and lie in the interval between 1.4 and 2.3 basis points. Only in the completely unrealistic scenario that unobserved variables were 24 times more important than all observed controls and fixed effects in our model, the interval would include zero, such that we would conclude that our estimated liquidity risk markup is driven by something other than liquidity risk.

In Panel (b) of Table 10 we report the bounds for different values of R^2_{max}, ranging from 0.25 to 0.40. These R-squares are large in light of the fact that we are trying to explain daily data

which is typically noisy. For comparison, Furfine (2001) achieves a maximum R^2 of 0.2 in his regression model for interest rates in the U.S. unsecured interbank market. Even in the most conservative case choosing $R^2_{max} = 0.4$, the borrower markup is in the interval 1.4 to 3.0 basis points, that is, still positive and close to our original estimate. Overall, the results show that our quantification of the borrower markup is robust to the presence of unobservable omitted variables.

Table 10: Bounding the effect of unobservable variables

This table presents results of the analysis of the potential effect of omitted variables on the estimated liquidity risk markup, β, using the methodology of Oster (2019). Panel (a) shows the one-step regression results for the parameter choices recommended by Oster (2019): $\delta = 1$ and $R_{max} = 0.31$. This parameter choice is conservative as it implies that potential unobserved variables are equally important as observed variables. Column (1) shows the baseline regression results without control variables ($r^e_{i,t} = \beta\ MOS_{i,t} + \varepsilon_{i,t}$). Column (2) presents the results when including the full set of control variables ($r^e_{i,t} = \beta\ MOS_{i,t} + X_{i,t}\ \theta + \eta_i + \lambda_t + \varepsilon_{i,t}$). Column (3) shows the main result of the analysis, that is, the identified set of values for the funding liquidity risk markup when allowing for potential omitted variables. Column (4) shows the value of δ which would lead an identified set so large that it includes $\beta = 0$ given $R_{max} = 0.31$. All results are computed using the Stata package psacalc. In Panel (b) we repeat the analysis for different plausible values of R_{max} based on the previous literature, ranging from 0.25 to 0.40.

Panel (a)

	(1) Uncontrolled	(2) Controlled	(3) Identified set	(4) δ for $\beta = 0$
β	1.431^{***}	2.005^{***}	[1.431;2.337]	24.08
	(18.64)	(10.12)		
NT	11,486	11,486		
R^2	0.029	0.240		

Panel (b)

	$R_{max} = 0.25$	$R_{max} = 0.30$	$R_{max} = 0.35$	$R_{max} = 0.40$
Identified set	[1.431;2.045]	[1.431;2.282]	[1.431;2.587]	[1.431;2.986]
δ for $\beta = 0$	55.17	26.58	17.51	13.05

6. Policy implications

Our findings have implications for banks, regulators, academia, and monetary policy. First, for individual banks, our results emphasize the importance of sophisticated liquidity management. Since it is costly to demand immediacy following liquidity shocks, banks must account for these additional costs in their business decision—for example, through liquidity transfer pricing. Quantifying the cost of funding immediacy enables banks to understand the trade-off between larger liquidity buffers and the need to be more aggressive to obtain funding. Thus, the findings from our paper can help to build a sounder practice for the management of liquidity risk, as

stressed in IOSCO (2012). Specifically, our measure should support banks in setting up adequate systems and procedures for timely identifying, measuring, and monitoring liquidity risks.

Second, accounting for the aggregate level of the funding liquidity risk markup is important for academics examining interest rate spreads in short-term funding markets. We show that not only premia demanded by lenders determine these spreads, but also markups paid by borrowers due to liquidity risk. Neglecting the role of borrowers could bias the interpretation of empirical results related to interest rate spreads.

Third, for policymakers, aggregate measures of the funding liquidity risk markup can serve as an indicator of market-wide liquidity stress and effectiveness of policy measures. Commonly used measures for liquidity stress such as Libor-OIS or TED spreads are no pure measure of (funding) liquidity risk, but bundle various kinds of risks including credit risk and rollover risk. As a consequence, the Libor-OIS spread can give misleading signals about liquidity risk. To show this, we construct an aggregate measure of funding liquidity risk based on our methodology and compare it to the Libor-OIS. A simple way to obtain such a measure is to compute the funding cost differential between banks with high and low liquidity risk, that is, the difference between the upper and lower rates in Panel B of Figure 1.

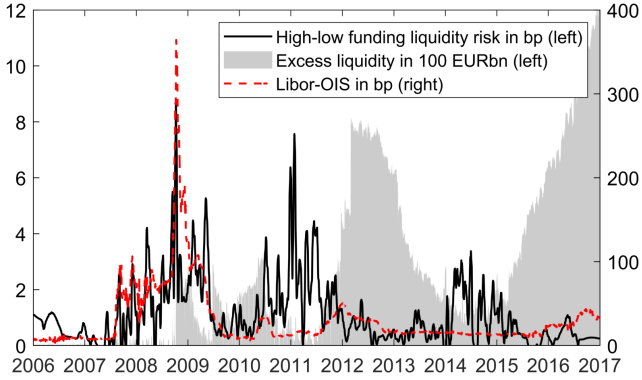
Figure 8 shows the evolution of our aggregate measure compared to the Libor-OIS spread and the excess liquidity in the Eurosystem, which captures the overall liquidity and monetary conditions. While both the Libor-OIS spread and our measure are high during the global financial crisis, only our measure exhibits a coherent pattern over the entire sample period. For instance, our measure increases at the height of the European sovereign debt crisis in 2011 when excess liquidity is relatively low; but it subsequently decreases in response to the ECB liquidity provisions such as the ECB's long-term refinancing operations (LTROs). In contrast, the Libor-OIS spread remains at low levels from 2010 on. The consistent increase of our measure in periods of funding strains and its decrease with liquidity provisions by central banks reiterate the importance of the funding liquidity risk channel and the overall validity of our measure.

Fourth, cross-sectional differences in the funding liquidity risk markup reveal *who* has a liquidity need or surplus. This is relevant for policy makers, but also for market infrastructure providers such as exchange systems and related clearing houses. For policy makers, it facilitates distinguishing between insolvent and illiquid banks, which is important as both require different policy responses. For clearing houses, assessing clearing members' liquidity risk may help prevent negative consequences such as disorderly liquidation of collateral assets and contagion across firms. Measuring individual banks' funding liquidity risk markups helps identify and monitor banks that are prone to funding shocks on a daily basis, which is not feasible with existing bank-level measures that rely on (annual) balance sheet data. Moreover, our measure is market-based, meaning that we do not need structural assumptions, for example, at which weights assets and liabilities of any kinds and maturities translate into cash.

Understanding cross-sectional differences in the funding liquidity risk markup is also crucial

Figure 8: Aggregate measure of the funding liquidity risk markup

Figure 8 compares an aggregate measure of the funding liquidity risk markup (solid line) with the Libor-OIS spread (dashed line). Our aggregate measure is constructed as the 20-day moving average of the funding cost differential between banks with high and low liquidity risk. For comparison, the figure also includes aggregate excess reserves in the Eurosystem, which are defined as deposits at the ECB deposit facility net of the recourse to the marginal lending facility, plus current account holdings in excess of those contributing to the minimum reserve requirements.



for central banks as heterogeneous funding costs adversely affect the pass-through efficiency of monetary policy. Internal operations, such as liquidity transfer pricing and funding value adjustments, create a channel through which inefficient liquidity management impacts investment decisions, pricing, and loan extensions. Therefore, banks may pass-through the differences in funding costs to their clients, such that heterogeneity spreads outside funding markets.

7. Conclusion

We propose and test the funding liquidity risk channel, which posits that borrowers with high liquidity risk are willing to pay a markup to lock in their funding. On this account, liquidity risk is factored into short-term interest rates via the borrowing side rather than the lending side, which is usually the focus of the literature. Borrowers with high liquidity risk are willing to pay, on average, two basis points more on a given day than their low-risk peers. This corresponds to an increase in nominal funding costs of over 2.5% for an increase in liquidity risk by one standard deviation. We also reveal that liquidity risk differs systematically and persistently across banks, thereby leading to systematic and persistent heterogeneity in funding costs. Our findings complement the existing literature on short-term interest rates, which emphasizes the role of lenders by examining the premia they require as compensation for credit and market liquidity risk.

Further, we are able to quantify the funding liquidity risk markup by exploiting the market

design of the European interbank repo market. However, it seems likely that our results have external validity for other short-term debt markets, in particular for the GCF repo market in the U.S., which has similar characteristics as the CCP-based European repo market. Unfortunately, there is often a lack of order submission data for other markets. For example, data on unsecured money markets in Europe and the United States usually come from settlement data, which do not provide information about order submissions. Even trade repository data and data collected due to new regulatory initiatives—for example, EMIR for derivatives—do not provide this information. Given the importance of liquidity risk, this calls for an expansion of reporting requirements. The investigation of the magnitude of borrower markups in other funding markets is a subject for future research.

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Appendix A.

A.1. Variable description

Table A.1: Variable descriptions

Table A.1 describes the variables used in the regression analysis.

Variable	Description	Frequency	Source
Excess rate	Repo rate over the daily volume-weighted average (in basis points)	daily	Eurex Repo
RF	Relative frequency of having a positive excess rate	daily	Eurex Repo
LiquidityRisk	Proxy for banks' idiosyncratic funding liquidity risk	daily	Eurex Repo
Volume	Trading volume (in million EUR)	daily	Eurex Repo
TradeTime	Volume-weighted average trading time (in decimals)	daily	Eurex Repo
Experience	Cumulated number of trading days	daily	Eurex Repo
TotalAssets	Size of total assets (in billion EUR)	yearly	SNL Financial
ROAA	Return on average assets (in decimals)	yearly	SNL Financial
Leverage	Debt-to-equity ratio (in decimals)	yearly	SNL Financial
CDS	CDS spreads	daily	Bloomberg

Does Quantitative Easing mitigate the Sovereign-Bank Nexus?

Alexander Bechtel, Jens Eisenschmidt, Angelo Ranaldo

Abstract

The credit risk of the sovereign affects the financial health of its banking sector and vice versa, creating an adverse feedback loop known as "sovereign-bank nexus". We show that Quantitative Easing can effectively mitigate the sovereign-bank nexus. Our results indicate that the ECB's Public Sector Purchase Programme reduced the co-movement of sovereign and bank credit risk by almost 80%. The mitigation is driven by the euro area periphery and works through three channels: (i) a reduction in government bond holdings of banks, (ii) an increase of government bond prices, and (iii) an increase in excess liquidity holdings of banks.

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1. Introduction

Sovereign and bank credit risks do not only increase individually during crises, they also reinforce each other leading to adverse feedback effects or "diabolic" loops. The origins and dynamics of these loops, also known as "sovereign-bank nexus" (nexus), have been studied extensively. Likewise, policy responses aiming at eliminating or mitigating the nexus have received significant attention in the literature, pointing to a mixed track record.[1] Nevertheless, we know little about the effectiveness of policies that do not aim to address the nexus directly, but which are operating on all important dimensions affecting it. Large-scale government bond purchases by central banks, also known as Quantitative Easing (QE), are a case in point as they tend to affect the price and volume of outstanding sovereign debt as well as banks and their balance sheets. Surprisingly, even though QE has arguably been one of the most important policy tools of the last decade, its impact on the nexus has, to the best of our knowledge, never been systematically studied. This paper aims to close this gap.

We show that QE can effectively mitigate the nexus. We analyze the effect of government bond purchases in the euro area and show that the Public Sector Purchase Programme (PSPP) of the European Central Bank (ECB) has significantly attenuated the nexus. The co-movement of sovereign and bank credit risk decreased by almost 80% after the start of the PSPP in March 2015. This reduction is mainly driven by the euro area periphery. The transmission channels that mitigate the feedback loop between sovereign and bank credit risk are (i) a reduction in government bond holdings of banks, that is, banks are less exposed to their sovereign, (ii) an increase of government bond prices, that is, banks' equity position improves, reducing banks' riskiness, and (iii) an increase in excess liquidity holdings of banks, that is, banks decrease their holdings of a risky asset (euro area periphery government bonds) and increase their holdings of a riskless asset (central bank reserves).[2]

The close link between sovereign and bank risk was laid bare during the global financial crisis 2007–2009 and in particular during the European sovereign debt crisis 2009–2012. This interlinkage has proven to be an important source of systemic risk, aggravating existing vulnerabilities and leading to adverse feedback loops between sovereign and bank risk. In Greece, the deteriorating sovereign creditworthiness became a solvency issue for the banking sector. In Ireland, the dynamics worked in the opposite direction, with risks in the financial sector spilling over to the sovereign. In both cases, sovereign and bank credit risk started to co-move in vicious

[1] See Fratzscher and Rieth (2019) for a recent literature review.

[2] We define excess liquidity as banks' recourse to the current account and deposit facility less the minimum reserve requirement.

circles.

The nexus has become even more relevant in light of the current economic crisis that has been triggered by the outbreak and the spread of the coronavirus (COVID-19). In response to the crisis, many governments embarked on massive stabilization efforts through government spending that increased public debt and concomitantly sovereign risk. Simultaneously, credit risk in the banking sector has increased considerably in light of the uncertain economic outlook and potential future losses. This raises concerns about a strong revival of the nexus. Central banks try to address the economic fallout from COVID-19 and its impact on banks and financial markets by extending existing unconventional policies or even by introducing entirely new, dedicated programs such as the ECB's Pandemic Emergency Purchase Programme (PEPP).

The close link between sovereign and bank credit risk originates from implicit or explicit public guarantees to banks and from the typically significant domestic government bond holdings of the banking sector (e.g., Acharya, Drechsler, and Schnabl, 2014; Gennaioli, Martin, and Rossi, 2014; Leonello, 2018; Dell'Ariccia et al., 2018). QE affects the nexus directly and indirectly. The direct effect of QE on the nexus is that it reduces the amount of government bonds owned by banks while simultaneously increasing the value of sovereign debt that remains on banks' balance sheets and increasing banks' holdings of risk-free central bank reserves. All these effects work in the direction of lowering the overall riskiness of banks emanating from their sovereign bond holdings. Therefore, through the direct channel, QE should mitigate the feedback loop between sovereign and bank credit risk by weakening the link between the two sectors.

The indirect effect of QE on the sovereign-bank nexus works through the impact of QE on banks' balance sheet positions that are not directly related to banks' holdings of sovereign bonds. The overall sign of the indirect effect is unclear. On the one hand, QE should further decrease banks' riskiness through its positive effect on economic activity, leading to lower loan loss provisions and higher credit demand, contributing to an improvement of the equity position of banks. This should in turn weaken the link between the sovereign and its banks (e.g., Altavilla, Boucinha, and Peydró, 2018). On the other hand, QE lowers long-term yields and induces bank risk taking (search-for-yield) and this effect should decrease banks' equity exposing banks more to a deterioration in the credit risk of their sovereign (e.g., Kurtzman, Luck, and Zimmermann, 2018; Darracq Pariès, Körner, and Papadopoulou, 2019; Crosignani, Faria-e Castro, and Fonseca, 2020). Consequently, while the direct effect immediately and automatically mitigates the link between banks and their sovereign, the two indirect effects might offset each other and only become effective with some delay.

In our empirical analysis, we provide evidence for the effects of QE on the nexus. We concentrate on measuring the impact of the direct effects while controlling for the indirect

effects. To this end, we follow and extend the methodology of Acharya, Drechsler, and Schnabl (2014), who examine the link between sovereign and bank credit risk in Europe during the Global Financial Crisis and the European Sovereign Debt Crisis 2007–2011. We exploit data on sovereign and bank CDS spreads between January 2014 and December 2016. Before the start of the PSPP on 9 March 2015, a 10% increase in the sovereign CDS spread leads to a 1.2% increase in the bank CDS spread. In the post-PSPP period, a 10% increase in the sovereign CDS spread only leads to a 0.2% increase in the bank CDS spread. This amounts to a reduction in the co-movement between sovereign and bank credit risk by almost 80%. It is noteworthy that the nexus is mitigated, even though both sovereign and bank credit risk individually increase after the start of the PSPP. This indicates that the direct effect of QE is the dominant force because the indirect effect relies on an improvement of general economic conditions. Our results also indicate that the sovereign-bank nexus as well as its mitigation is mainly driven by the euro area periphery.

We provide additional evidence for the different channels through which QE mitigates the nexus directly, namely a (i) decrease in government bond holdings, (ii) increase in government bond prices, and (iii) increase in excess liquidity holdings. To this end, we sort banks according to the fraction of their bond portfolio sold during the PSPP, their pre-PSPP government bond holdings, and their increase in excess liquidity holdings. We find that the co-movement of sovereign and bank credit risk is reduced especially for banks that (i) sell a bigger fraction of their bond portfolio, (ii) hold more government bonds before the start of the PSPP (and hence are more affected by subsequent changes in prices), and (iii) increase their excess liquidity holdings more. This indicates that all three channels that represent the direct effect of QE on the nexus are active.

We contribute to two strands in the literature: First, we add to existing research on the sovereign-bank nexus. Allen et al. (2018) show that public guarantees can affect banks' liquidity creation and the likelihood of runs. Gennaioli, Martin, and Rossi (2014) present a model in which government default dries up banks' liquidity and therefore the government's incentive to bail out banks depends on banks' holdings of public bonds. Furthermore, banks' anticipation of government bailouts disincentives equity issuance and incentivizes them to invest into government debt (Cooper and Nikolov, 2018).

Acharya, Drechsler, and Schnabl (2014) take banks' government bond holdings as given and build a theoretical model of the two-way feedback loop between financial sector and sovereign credit risks. On the one hand, financing bailouts is costly because increased taxation induces the corporate sector to underinvest, which in turn erodes the creditworthiness of the sovereign. On the other hand, higher sovereign credit risk feeds back into the financial sector holding a

significant share of government debt and reliant on government guarantees. Farhi and Tirole (2018) add a cross-border dimension to the sovereign-bank nexus. In their model, sovereigns anticipate assistance or debt forgiveness from foreign investors because these investors would suffer from a collateral damage in case of a default. This creates a moral hazard because sovereigns are less incentivized to control the banking sector tightly as they share risks with others. We contribute to this literature by clearly documenting that flagship central bank policies aimed at easing monetary policy (QE in our case) can have, as a side effect, a powerful mitigating impact on the nexus.

Second, we contribute to the literature on the effects of QE on financial markets. This literature usually focuses on the transmission channels of large-scale government bond purchases to government bond yields (e.g., Gagnon et al., 2011; Krishnamurthy, Nagel, and Vissing-Jorgensen, 2018). There is little evidence, however, on the effect of QE on financial stability, especially on the feedback loop between sovereign and bank risk. Fratzscher and Rieth (2019) provide empirical evidence for a two-way causality between sovereign risk and bank risk in the euro area, taking into account various unconventional monetary policies, such as the ECB's longer-term refinancing operations. On the other hand, the central bank support can create unintended, adverse effects such as excessive illiquid leverage in the financial sector (Acharya and Tuckman, 2014), delayed portfolio adjustments of worthless assets (Bolton, Santos, and Scheinkman, 2009), and a disincentive to sell illiquid assets (Diamond and Rajan, 2011). We contribute to this literature by examining, for the first time, the impact of QE on the sovereign-bank nexus. Additionally, we provide empirical evidence for the channels through which QE affects the nexus, pointing at the important impact of portfolio rebalancing: A substitution of government bonds with central bank reserves can act as a circuit breaker for the nexus. However, this link is not mechanical. In order to conclude that QE mitigates the nexus, it is not sufficient to document that the banking sector reduces its exposure to government bonds.[3] The nexus could remain prevalent if banks rebalance into risky private securities in a search for yield. Alternatively, banks might also adjust the composition of their government bond holdings increasing their exposure to peripheral bonds in a "carry trade"-fashion as shown by Acharya and Steffen (2015). Our contribution is to provide empirical evidence for the mitigating effect of the PSPP on the nexus and to quantify its magnitude. Finally, Christensen and Krogstrup (2018) examine the role of central bank reserves in the transmission of QE.

The remaining paper is structured as follows: In Section 2, we present the channels through which QE mitigates the sovereign-bank nexus. Section 3 provides empirical evidence for the mitigating effect of QE on the nexus. Finally, in Section 4, we discuss several policy implications

[3]See Koijen et al. (2020) for a study on rebalancing behavior of banks in the euro area during the PSPP.

of our findings and in Section 5, we conclude.

2. Channel

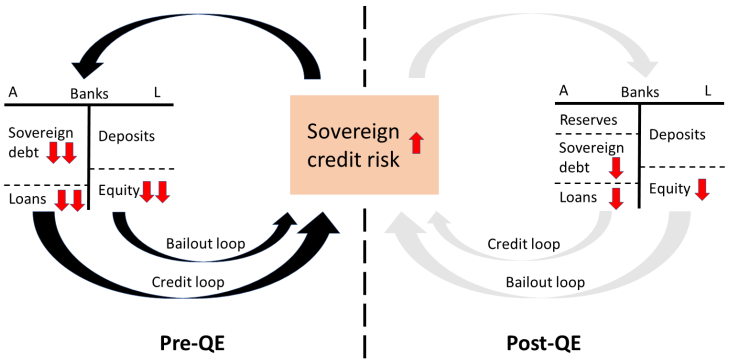
2.1 Intuition

Figure 1 illustrates the channels through which QE can mitigate the sovereign-bank nexus. The left panel shows the feedback loop between bank and sovereign credit risk before the start of large-scale government bond purchases. The top arrow illustrates the first part of the sovereign-bank feedback loop. It shows how sovereign risk can be transmitted to bank risk through the sovereign debt holdings of banks: An increase in sovereign credit risk reduces the value of banks' holdings of sovereign debt and acts as a shock to banks' equity. The quality of the loan portfolio of the bank might also suffer from the shock to sovereign risk. This increases the debt-to-equity ratio further and puts additional pressure on the solvency of the bank.

The arrows at the bottom of Figure 1 illustrate how the decreased solvency of banks feeds back to sovereign credit risk. There are two channels: First, the reduced solvency of the banking sector increases the probability that banks have to be bailed out. A higher likelihood of bank bailouts worsens the sovereign creditworthiness, creating a bailout loop. Second, the reduced solvency and increased leverage of banks hampers credit creation and therefore lowers investment, economic growth, and tax revenue. This weakens the solvency of the government, creating a credit or real-economy loop.

Figure 1: Sovereign-bank nexus: Feedback channels

Figure 1 illustrates the channels through which sovereign risk and bank risk are interrelated and how this interrealtion is affected by QE. It is inspired by Brunnermeier et al. (2016).



The right panel of Figure 1 illustrates the situation after the central bank has started large-scale government bond purchases. During this process, banks sell government bonds to the central bank in return for default-free central bank reserves, which end up as excess liquidity on banks' balance sheets.

This portfolio rebalancing—which we call the direct effect of QE—weakens the feedback loop between sovereign and bank credit risk for three reasons: First, domestic government bond holdings constitute a lower fraction of banks' balance sheets. Consequently, a shock to sovereign credit risk has a smaller effect on banks' equity and hence their leverage and solvency. This alleviates the bailout and credit loop and thus mitigates the sovereign-bank nexus as a whole. Second, the large-scale government bond purchases of the central bank lead to an increase in government bond prices. This has a direct positive effect on the equity of banks, as banks hold significant amounts of government bonds. Third, QE increases banks' holdings of central bank reserves. Reserves are a default-free, safe asset that is uncorrelated with the risk profile of other assets on banks' balance sheets. Consequently, an increasing fraction of reserve holdings makes the balance sheet of a bank more robust and hence mitigates the exposure of banks to credit risk shocks.

2.2 Balance sheet model

We can formalize the direct effect of QE on the sovereign-bank nexus in a simple balance sheet model. The assets of the banking sector consist of government bonds G, central bank reserves R, and loans to the economy L. These assets are financed through deposits D and equity E:

$$E = G + R + L - D. \tag{1}$$

We can rewrite the nominal amount G as $P_G Q_G$, where P_G denotes the price of the bonds and Q_G the outstanding amount.

In this simple setting, a shock to sovereign credit risk, that is, a shock to P_G, has the following effect on the equity of the banking sector:

$$\frac{\partial E}{\partial P_G} = Q_G. \tag{2}$$

This enables us to make two statements about the effect of QE on the sovereign-bank nexus: First, the positive sign of the derivative shows that an increase in government bond prices triggered by QE has a positive effect on the equity of banks. This makes the balance sheets of banks more robust to exogenous shocks and hence should mitigate the nexus. Second, the derivative shows that the magnitude of the effect of bond prices on bank equity depends on

the size of the domestic government bond holdings. Since these holdings decrease due to QE, a potential negative shock to sovereign risk has less severe consequences to banks' equity. This should also mitigate the nexus.

QE does not only reduce the government bond holdings of banks, it also increases their excess liquidity holdings. Additional excess liquidity makes the balance sheet of a bank more robust. In order to measure the stability of banks' balance sheets, we compute the capital adequacy ratio (CAR), which is defined as the ratio of equity over risk-weighted assets (RWA):

$$CAR = \frac{\text{E}}{\text{RWA}}, \tag{3}$$

where RWA $= \omega_L L + \omega_G G + \omega_R R$. We assume the following ranking for the risk weights of loans, government bonds, and reserves, respectively: $\omega_L \geq \omega_G \geq \omega_R = 0$. Hence, loans are more risky than government bonds, which are more risky than central bank reserves. Note, that our CAR measure should be interpreted as one that reflects actual credit risk of financial assets, such as the measures used by banks internally. We abstract from the zero risk weights attached to government bonds in the current regulatory framework.

During QE, RWA decrease because G decreases and R increases. Consequently, the CAR increases creating a bigger "cushion" for potential losses. Equation (3) also enables us to show that the sensitivity of the CAR with respect to government bonds negatively depends on the risk weight of these bonds:

$$\frac{\partial \text{CAR}}{\partial G} = -\omega_G \frac{E}{(\omega_L L + \omega_G G + \omega_R R)^2} \leq 0. \tag{4}$$

Consequently, selling government bonds during QE is particularly helpful if these bonds have a high risk weight.

In sum, government bond purchases increase the stability of banks' balance sheets by increasing the share of risk-free assets. Banks' balance sheets become more robust to exogenous shocks, which helps to mitigate the sovereign-bank nexus. The mitigation is particularly big if the central bank purchases risky assets.

3. Empirical Analysis

3.1 Data and summary statistics

In order to test whether the PSPP mitigates the nexus, we collect daily observations of sovereign and bank CDS spreads between 1 January 2014 and 31 December 2016. The dataset covers 58 banks located in 11 different euro area countries, including Austria, Belgium, Finland, France,

Germany, Greece, Italy, Ireland, the Netherlands, Portugal, and Spain. We complement this data with monthly balance sheet information and daily excess liquidity holdings from proprietary datasets at the European Central Bank. Our sample of 58 banks captures about 40% of total bank assets in the 11 countries. The 30 banks from the euro area periphery—which receive a special focus in our empirical analysis—have a market share of more than 47%.

The Public Sector Purchase Programme (PSPP) was announced on 22 January 2015 and started on 9 March 2015. Under the PSPP, the ECB purchases bonds of euro-area governments, agencies, and European institutions. Until the end of 2016, the total purchase volume amounted to EUR 1,273 billion, corresponding to a monthly purchase volume of about EUR 60 billion. Purchases ware allocated across euro area member countries according to their capital key at the ECB.[4]

Table 1 presents summary statistics for all variables in our analysis. We split the dataset into two periods, pre- and post-PSPP. Not surprisingly, bank CDS spreads are higher than sovereign CDS spreads in both periods. Additionally, average CDS spreads as well as their variation increases post-PSPP indicating higher general risk in this period. This is also in line with our aggregate measures for volatility (VDAX-NEW) and credit risk (iTraxx Europe). The VDAX-NEW measures the implied volatility of the German stock market index DAX. The iTraxx Europe is a CDS market index and consists of 125 highly liquid European entities with investment grade credit ratings as published by Markit.

The summary statistics illustrate an important point: A mitigation of the nexus does not necessarily imply a general improvement in bank and sovereign credit risk. The nexus concerns the feedback loop between these risks and not their levels. Hence, an increase in bank and sovereign credit risk post-QE does not exclude a mitigation of the feedback loop between these two risks through the direct effects of QE, that is, via reduced government bond and increased excess liquidity holdings as well as through higher government bond prices. Only the indirect effects of QE require an improvement of general economic conditions and perceptions of risk in the banking sector in order to be effective. The summary statistics do not support this. Also, balance sheet statistics such as the share of capital (capital over total assets) and the share of non-performing loans do not paint a clear picture. While the capital share increases by about 1.2 percentage points post-QE, the share of non-performing loans also increases (by 1.5 percentage points). This indicates that loan portfolios did not get more healthy post-QE and hence did not contribute to a mitigation of the feedback loop between sovereign and bank credit risk. We still control for indirect effects in our empirical analysis.

[4]For more information about the PSPP, see `https://www.ecb.europa.eu/mopo/implement/omt/html/pspp.en.html`.

Table 1: Summary statistics

Table 1 presents summary statistics for all variables. Panel (a) covers the pre-PSPP period from 1 January 2014 to 8 March 2015. Panel (b) covers the post-PSPP period from 9 March 2015 - 31 December 2016. All shares are computed as shares of total assets. N is the number of banks for which data on the respective variable is available.

(a) Pre: 1 Jan 2014 - 8 March 2015

	Mean	Std	Min	Max	N
Bank CDS	180	182	37	2,310	58
Sovereign CDS	114	209	16	2,272	58
Foreign Exposure CDS	5.03	2.92	0.78	19.40	58
Share domestic bond (%)	5.63	3.27	−0.18	16.19	39
Share excess liquidity (%)	0.22	0.55	−0.23	4.78	39
Capital share (%)	11.35	5.29	3.07	23.42	32
Loan book share (%)	38.86	14.65	10.69	63.37	32
NPL share (%)	8.53	7.66	1.78	30.89	32
VDAX-NEW	18.35	3.10	12.17	28.66	–
iTraxx Europe	65.01	7.41	47.67	85.23	–

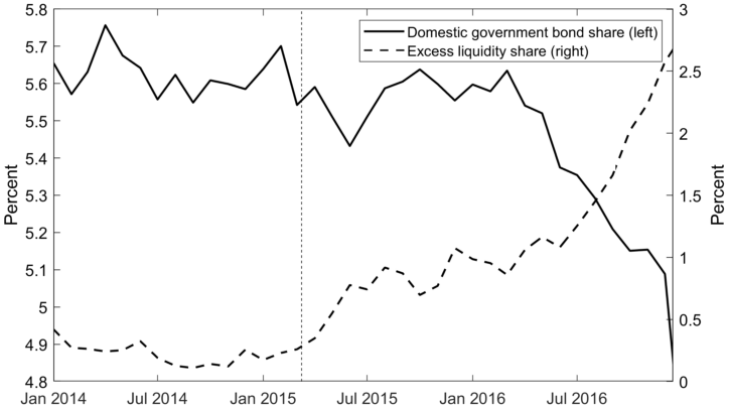
(b) Post: 9 March 2015 – 31 Dec 2016

	Mean	Std	Min	Max	N
Bank CDS	274	475	24	7,423	58
Sovereign CDS	169	468	12	8,533	58
Foreign Exposure CDS	5.12	3.51	0.65	25.63	58
Share domestic bond (%)	5.46	3.18	−0.02	16.60	39
Share excess liquidity (%)	1.11	1.89	−0.25	10.80	39
Capital share (%)	12.51	6.08	3.50	27.89	32
Loan book share (%)	39.42	12.88	12.32	59.07	32
NPL share (%)	9.96	6.08	3.50	27.89	32
VDAX-NEW	23.35	4.56	14.73	38.29	–
iTraxx Europe	74.10	11.94	49.38	125.70	–

Figure 2 plots the domestic government bond and excess liquidity holdings as a share of banks' balance sheets. These are the variables behind the direct effect of QE on the nexus. The figure shows that euro area banks reduce their government bond and increase their excess liquidity holdings after the start of the PSPP. The dashed vertical line marks the start of the PSPP purchases on 9 March 2015. Until the end of 2016, the average share of government bond holdings of banks' balance sheets decreases from about 5.6% to below 5%. At the same time, the share of excess liquidity holdings increases from below 0.5% to more than 2.5%. The reduction in government bond holdings kicks in with a slight delay because in the first months of the program, foreign institutions, which are not part of our sample, were the main sellers of government bonds to the ECB (Koijen et al., 2020).

Figure 2: Domestic government bond and excess liquidity holdings

Figure 2 plots the average domestic government bond and excess liquidity holdings of banks as a share of total asset. The figure is based on proprietary balance sheet datasets from the European Central Bank.



3.2 Identification strategy

The main challenge when testing whether QE mitigates the sovereign-bank nexus is to identify the direct link between sovereign and bank credit risk. Hence, we have to control for other (unobserved) factors that contemporaneously impact both risks, such as regulation or changes in macroeconomic risk. For instance, changes in expectations about economic growth or employment might lead to changes in sovereign credit risk and at the same time have direct effects on banks' loan and mortgage portfolios. This could lead to a co-movement between sovereign and bank credit risk without there being a direct link between the two.

We address this challenge by employing four sets of control variables. First, we capture changes in variables that have market-wide effects on the financial sector by including day fixed effects. Hence, we control for all macro variables and changes in regulation that contemporaneously affect bank and sovereign credit risk.

Second, we control for the exposure of each country's banking sector to foreign credit risk. To this end, we create a foreign exposure measure, which captures changes in banks' credit risk due to changes in sovereign credit risk of foreign countries. We compute this measure as the weighted average of foreign countries' CDS spreads. The weights are based on the size of the foreign exposure relative to the total size of a country's banking sector. Foreign exposures are available in the consolidated banking statistics of the Bank for International Settlements.[5] The

[5]See, `https://www.bis.org/statistics/consstats.htm`.

total sizes of euro area sovereign banking sectors are retrieved from the ECB's MFI balance sheet items via the Statistical Data Warehouse.[6]

Third, we control for heterogeneity in the exposure of banks to changes in macroeconomic variables and regulation. To this end, we include bank fixed effects as well as an aggregate measure for volatility (VDAX-NEW) and credit risk (iTraxx Europe). In case of the VDAX-NEW and the iTraxx Europe, we allow for bank-specific coefficients by interacting the indices with our bank fixed effects. The VDAX-NEW captures changes in expectations about aggregate volatility, which are pivotal for the pricing of credit risk. The iTraxx Europe captures variation in CDS spreads that might be caused by shocks specific to the CDS market or changes in market-wide credit risk and liquidity.

Fourth, we control for the indirect effects of QE on the nexus by adding balance sheet variables. In particular, we include banks' capital share (capital over total assets) to ensure that the mitigation of the nexus is not driven by deleveraging. We include loan book shares (loans over total assets) to control for an increase in credit demand. And we include the shares of non-performing loans (non-performing loans over total assets) to control for changes in the quality of the loan portfolio.

We estimate the following regression:

$$\begin{aligned}\Delta\log(\text{Bank CDS}_{ijt}) = \; & \alpha_i + \delta_t + \beta\Delta\log(\text{Sovereign CDS}_{jt}) + \\ & \gamma\Delta\log(\text{Foreign Exposure CDS}_{ijt}) + \rho_i\Delta X_{ijt} + \kappa\Delta Z_{ijt} + \varepsilon_{ijt},\end{aligned}$$

where $\Delta\log(\text{Bank CDS}_{ijt})$ is the daily change in logged CDS spreads of bank i located in country j, $\Delta\log(\text{Sovereign CDS}_{jt})$ is the daily change in logged CDS spreads of sovereign j, $\Delta\log(\text{Foreign Exposure CDS}_{ijt})$ is the daily change of the foreign exposure measure, and ΔX_{ijt} captures daily changes of aggregate volatility (VDAX-NEW) and the CDS market index (iTraxx Europe), whereby we allow for bank-specific coefficients ρ_i. Finally, ΔZ_{ijt} captures the quarterly balance sheet control variables, α_i are bank fixed effects, and δ_t are time fixed effects. We cluster the standard errors at the bank level.

3.3 Results

Table 2 presents the results. We investigate the link between sovereign and bank credit risk separately before and after the start of the PSPP. Columns (1) to (3) cover the pre-PSPP period from 1 January 2014 to 8 March 2015 and Columns (4) to (6) the post-PSPP period from 9 March 2015 to 31 December 2016. For each period, we present the results with and without

[6] See, `https://sdw.ecb.europa.eu/browse.do?node=9691312`.

bank fixed effects, balance sheet controls, and bank-specific coefficients on the CDS market and volatility index.

In the pre-PSPP period, we find a positive and statistically as well as economically significant relation between sovereign and bank credit risk. A 10% increase in the sovereign CDS price leads to a $0.8 - 1.2\%$ increase in the bank CDS spread. This result is robust to including bank-specific controls and suggests there was a feedback loop between bank and sovereign credit risk before the introduction of the PSPP. The size of the effect is similar to the findings of Acharya, Drechsler, and Schnabl (2014) for European banks and sovereigns in the years after the global financial crisis.

In the post-PSPP period, the coefficient is still positive and statistically different from zero, but it has decreased by almost 80%. A 10% increase in sovereign CDS spreads only leads to $0.2 - 0.5\%$ increase in bank CDS spreads. Recall, that we control for the joint variation of macroeconomic variables and for bank-specific exposure to aggregate volatility and the CDS market. Consequently, it is unlikely that the co-movement between sovereign and credit risk is driven by market-wide shocks. Instead, these results provide empirical evidence for the mitigating effect of the PSPP on the sovereign-bank nexus. The results are also robust to including balance sheet control variables to control for potential indirect effects of QE. We leave out these control variables in our baseline specification and present the results separately in column (3) and (6) because the sample size is reduced significantly when including balance sheet variables.

Table 2: Change in Bank and Sovereign Credit Risk

Table 2 shows the effect of sovereign credit risk on bank credit risk before and after the introduction of the Public Sector Purchase Programme (PSPP). The sample with daily frequency covers 58 banks with publicly traded credit default swaps (CDS) from 11 different euro area countries. Columns (1) to (3) cover the pre-QE period (1 January 2014 to 8 March 2015) and columns (4) to (6) cover the post-QE period (8 March 2015 to 31 December 2016) for all banks in the sample. We add balance sheet control variables in columns (3) and (6), which reduces the sample size to 32 banks. Columns (7) to (10) distinguish between the origin of banks. *Core* captures banks from the core euro area, in particular from Austria, Belgium, Finland, France, Germany, and the Netherlands. *Periphery* includes banks from Greece, Italy, Ireland, Portugal, and Spain. ΔLog(Bank CDS) is the daily change in the natural logarithm of bank CDS. ΔLog(Sovereign CDS) is the daily change in the sovereign CDS of the country in which the bank is headquartered. We add a range of control variables, including bank and day fixed effects, the foreign exposure measure ΔLog(Foreign Exposure CDS), and interactions of bank fixed effects with the change in the CDS market index and the change in the volatility index. t-statistics are in parentheses.

	Δ log(Bank CDS)									
	Pre-QE			Post-QE			Pre-QE		Post-QE	
	All	All	All	All	All	All	Core	Periphery	Core	Periphery
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Δ log(Sovereign CDS)	0.117	0.0804	0.111	0.0268	0.0178	0.0475	0.00368	0.152	0.00683	0.0347
	(4.83)	(3.79)	(2.06)	(2.35)	(2.41)	(1.94)	(0.14)	(5.00)	(0.62)	(3.58)
Time/Bank FE	Y/N	Y/Y	Y/Y	Y/N	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y
Foreign Exposure CDS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Bank-level betas	N	Y	Y	N	Y	Y	Y	Y	Y	Y
Balance sheet controls	N	N	Y	N	N	Y	N	N	N	N
Observations	17,806	17,806	1,413	27,550	27,550	5,612	8,596	9,210	13,300	14,250
Banks	58	58	32	58	58	32	28	30	28	30
R^2	0.151	0.193	0.402	0.181	0.242	0.388	0.239	0.202	0.383	0.211
Adjusted R^2	0.136	0.171	0.281	0.166	0.224	0.323	0.203	0.166	0.356	0.178

Columns (7) to (10) of Table 2 show that the co-movement of sovereign and bank credit risk is driven by countries and banks in the euro area periphery. Columns (7) and (9) show the pre- and post-QE relation between sovereign and bank CDS spread for 28 banks from the core euro area, that is, from Austria, Belgium, Germany, Finland, France, and the Netherlands. Columns (8) and (10) capture 30 banks from the euro area periphery, that is, from Ireland, Italy, Greece, Portugal, and Spain. There is no feedback loop between sovereign and bank credit risk in the euro area core, neither before nor after the start of the PSPP.

In the euro area periphery, on the other hand, the feedback loop is highly statistically as well as economically significant. A 10% increase in the sovereign CDS spread leads to a 1.5% increase in the bank CDS spread before the start of the PSPP. In the post-PSPP period, the effect is still positive and statistically different from zero, but it decreases to about 0.3%. These results support the concern that the sovereign-bank risk nexus is primarily a problem for the euro area periphery. However, they also suggest that large-scale purchases of periphery government bonds mitigate the feedback loop between sovereign and bank credit risk in these countries.

In the core-periphery analysis and all following empirical models, we do not include balance sheet controls because this would significantly reduce the number of observations. Table B.1 in the Appendix shows that all regression results hold if we include balance sheet controls. We provide additional evidence for the role of indirect effects of QE on the nexus in the Appendix. Overall, we find that indirect effects play a minor role for the nexus as already suggested by the summary statistics.

3.4 Additional evidence on the channels

In this section, we provide additional evidence for the direct effect of QE on the sovereign-bank nexus. We identified three mechanisms that directly alleviate the nexus: (i) reduction in domestic government bond holdings, (ii) increase in government bond prices, and (iii) increase in excess liquidity holdings. To provide additional evidence for these channels, we focus on periphery banks and rank these banks according to different criteria.

In order to test (i), we sort our banks according to changes in the share of domestic government bond holdings. We label the 50% of banks that reduce their portfolio of domestic government bonds most as *Top* and the 50% with the least reduction as *Bottom*. We expect the link between sovereign and bank credit risk to weaken more for banks that sell more government bonds.

In order to test (ii), we sort our banks according to their share of domestic government bond holdings pre-QE. To this end, we compute the average holdings share of our banks in the first six months of 2014. This ensures that our ranking is not affected by anticipation effects of the

PSPP. We label the 50% of banks that hold the biggest portfolio share of domestic government bonds as *Top* and the 50% with the lowest share as *Bottom*. We expect the link between sovereign and bank credit risk to weaken more for banks that hold the highest share of bonds because these banks profit most from price increases.

In order to test (iii), we sort our banks according to changes in the share of excess liquidity holdings. We label the 50% of banks that increase their excess liquidity most as *Top* and the 50% with the lowest increase as *Bottom*. We expect the link between sovereign and bank credit risk to weaken more for banks that increase their excess liquidity holdings more.[7]

Table 3 presents the results, including the full set of control variables. The sample includes 21 banks from 5 euro area periphery countries. Columns (1) to (4) present the results for the ranking of banks based on changes in sovereign bond holdings, columns (5) to (8) for the ranking based on pre-QE sovereign bond holdings, and columns (9) to (12) for the ranking based on changes in excess liquidity holdings. The results for the pre-PSPP period are in line with previous results. There is a strong link between sovereign and bank credit risk in the euro area periphery before the start of the PSPP. The only exception is the estimate for the pre-PSPP coefficient of *Top* banks when ranked according to the pre-QE government bond holdings (column (5)). The point estimate is similar to what we would expect, but it is not significant.

Post-QE, the link between sovereign and bank credit risk weakens across all banks. However, in line with our channels, the relation weakens particularly for banks that (i) strongly reduce their government bond holdings, (ii) hold a bigger portfolio of sovereign bonds pre-QE, and (iii) increase their excess liquidity holdings more. In all three cases the coefficient for *Top* banks post-QE is statistically not different from zero anymore. Consequently, these banks are not prone to the sovereign-bank risk nexus anymore.

[7]Note that a reduction in government bond holdings and an increase of excess liquidity are not necessarily two sides of the same coin. The bank that has sold government bonds to the central bank, might decide to lend the reserves to other banks via the interbank market.

Table 3: Change in Bank and Sovereign Credit Risk (top vs. bottom)

Table 3 shows the effect of sovereign credit risk on bank credit risk before and after the introduction of the Public Sector Purchase Programme (PSPP). The sample with daily frequency covers 21 banks with publicly traded credit default swaps (CDS) from 5 different euro area periphery countries. In column (1) to (4), we sort the banks according to their changes in government bond holdings. In column (5) to (8), we sort the banks according to their government bond holdings pre-QE. Finally, in column (9) to (12), we sort banks according to changes in excess liquidity holdings. *Top* captures the banks that reduce their government bond or excess liquidity holdings more than the median, or banks that hold more government bonds as the median pre-QE. Likewise, *Bottom* captures the banks that reduce their government bond (excess liquidity) holdings less than the median, or banks that hold less government bonds as the median pre-QE. Columns (1), (2), (5), (6), (9), and (10) cover the pre-QE period (1 January 2014 to 8 March 2015). Columns (3), (4), (7), (8), (11), and (12) cover the post-QE period (9 March 2015 to 31 December 2016). ΔLog(Bank CDS) is the daily change in the natural logarithm of bank CDS. ΔLog(Sovereign CDS) is the daily change in the sovereign CDS of the country in which the bank is headquartered. We add a range of control variables, including bank and day fixed effects, the foreign exposure measure ΔLog(Foreign Exposure CDS), and interactions of bank fixed effects with the change in the CDS market index and the change in the volatility index. t-statistics are in parentheses.

	Δ Log(Bank CDS)											
	Ranking: Δ Sov bond holdings				Ranking: Pre-QE sov bond holdings				Ranking: Δ EL holdings			
	Pre-QE		Post-QE		Pre-QE		Post-QE		Pre-QE		Post-QE	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Δlog(Sovereign CDS)	0.152	0.161	0.0218	0.0391	0.164	0.163	0.0185	0.0387	0.208	0.163	0.0199	0.0396
	(10.26)	(3.18)	(1.27)	(3.11)	(1.75)	(3.74)	(0.35)	(3.61)	(3.06)	(3.66)	(0.58)	(3.23)
Time/Bank FE	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y
Foreign Exposure CDS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Bank-level betas	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Balance sheet controls	N	N	N	N	N	N	N	N	N	N	N	N
Observations	3,070	3,377	4,750	5,225	3,377	3,070	5,225	4,750	3,377	3,070	5,225	4,750
Banks	10	11	10	11	11	10	11	10	11	10	11	10
R^2	0.444	0.224	0.341	0.277	0.271	0.364	0.512	0.322	0.266	0.367	0.558	0.302
Adjusted R^2	0.376	0.138	0.263	0.200	0.190	0.286	0.459	0.242	0.184	0.289	0.510	0.219

4. Policy implications

Our paper shows that the large-scale government bond purchases under the PSPP mitigates the sovereign-bank nexus in the euro area. This finding is important for policy makers (for example, central bankers, public debt managers, and fiscal policy advisors) and market participants, especially in light of recent economic and financial developments following the global spread of the coronavirus. A functioning banking sector is a prerequisite for the orderly transmission of monetary policy impulses. We show that large-scale asset purchases do not only provide additional stimulus in a situation in which short-term rates can no longer be used for that purpose, they also contribute to decoupling the banking sector risk from sovereign risk. This should be beneficial for the transmission of monetary policy, which is particularly relevant for peripheral euro area countries.

More generally, our results highlight the importance of large-scale government bond purchases for financial stability, in particular during crises. We show that QE can mitigate negative effects on financial stability of higher debt levels triggered by expansionary fiscal policy. Thereby, it can alleviate the diabolic loop between sovereign and bank credit risk.

These insights are also crucial for assessing the policy relevance of some new unconventional measures such as the Pandemic Emergency Purchase Program (PEPP) introduced by the ECB. It seems fair to assume a higher risk of sovereign downgrades due to the additional fiscal spending that the pandemic emergency will entail for some euro area countries.

5. Conclusion

Sovereign risk and banking risk are interlinked and mutually reinforcing. Understanding which factors determine the sovereign-bank nexus is important from many points of view, including fiscal policy, monetary policy and financial stability. This is particularly true in view of the economic and financial consequences that are emerging from the coronavirus (COVID-19) crisis.

The contribution of our work is to show that Quantitative Easing (QE) mitigates the sovereign-bank nexus. In a simple balance sheet framework, we show that a simultaneous reduction of banks' holdings of domestic government bonds and an increase in default-free central bank reserves alleviate the nexus.

We then analyze the Public Sector Purchase Programme (PSPP) conducted by the European Central Bank in the euro area and find that the sovereign-bank nexus decreases by almost 80% after the start of the PSPP. In line with our balance sheet model, the mitigation of the nexus is mainly driven by banks that are located in the euro area periphery. Our results further indicate that the direct effect of QE on the nexus is dominating and we provide evidence for

the three channels through which QE affects the nexus directly: We show that the nexus is mitigated especially for banks that (i) sell a bigger fraction of their bond portfolio, (ii) hold more government bonds before the start of the PSPP (and hence are more affected by subsequent changes in prices), and (iii) increase their excess liquidity holdings more.

Our findings highlight the importance of large-scale government bond purchases for financial stability. This area of research deserves more empirical and theoretical attention. Understanding the impact of QE on financial stability is crucial for a better understanding of the transmission mechanisms of QE, which are still openly debated in the literature. Finally, our findings may also be relevant for the burgeoning literature on zombie lending (e.g., Acharya et al., 2020a,b), which finds that undercapitalized banks lend on to weak firms and sovereigns. While we do not look at lending to firms, we clearly document that banks have reduced their lending to sovereigns—including the weaker ones in our sample—as a consequence of QE policies. Consequently, it would be interesting to explore the consequences of our findings for banks' lending decision to the corporate sector.

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Appendix B.

B.1. Additional potential confounders

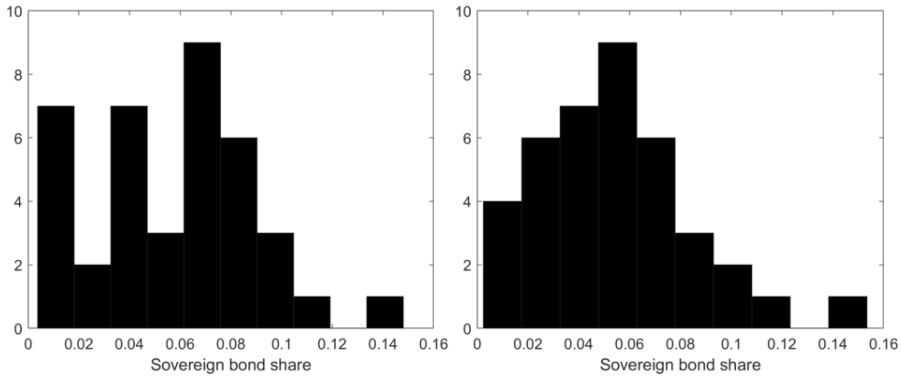
The PSPP coincided with other policies that might impact the relation between sovereign and bank credit risk through one of our channels. This concerns especially the introduction of the single supervisory mechanism (SSM) in September 2014 and other non-standard monetary policies such as targeted longer-term refinancing operations (TLTROs) and the negative interest rate policy (NIRP).

B.1.1 Single supervisory mechanism

The start of the SSM in September 2014 could affect our results as it may have led to a convergence of banks' domestic sovereign debt holdings across countries due to the centralisation of prudential supervision. While plausible, there is no evidence of a convergence of banks' sovereign debt holdings across euro area countries after the start of the SSM. Figure 2 shows that government bond holdings of banks remained stable in 2014. Additionally, Figure B.1 shows that marked differences in banks' propensity to hold government bonds remain after the start of the PSPP. If anything, banks should have had an incentive to reduce their sovereign bond holdings already before the start of the SSM in the wake of the so-called comprehensive assessment. This was conducted by the ECB and national supervisors to determine the asset quality of euro area banks, which were selected to be supervised by the SSM. The comprehensive assessment was finalized in December 2013, well before the start of the PSPP and to the extent that banks adjusted their positions to be seen in a more favourable light in the comprehensive assessment, any such adjustment will not affect our results as the PSPP only started in March 2015.

Figure B.1: Distribution of sovereign bond holding shares

Figure B.1 presents two histograms of the sovereign bond holding shares of banks before and after the start of the PSPP.



(a) Pre-PSPP **(b) Post-PSPP**

B.1.2 Targeted longer-term refinancing operations and negative interest rate policy

The PSPP was not the only non-standard measures taken by the ECB during the period in which we measure the effects of QE on the nexus. During our sample period, the ECB conducted so-called targeted longer-term refinancing operations (TLTROs) and intensified the use of its negative interest rate policy (NIRP). TLTROs are refinancing operations where the rate paid by banks for their central bank loans is only known ex-post and conditional on the banks meeting specific loan growth targets. For this reason, TLTROs are unlikely candidates to affect the nexus as banks engaging in sovereign bond purchases instead of lending to the private sector would risk paying a higher rate for their central bank loans. This renders a simple sovereign carry strategy unattractive. Furthermore, the first TLTRO program—decided in June 2014 and starting with two entry operations in September and December 2014—pre-dates our sample. If banks did not participate in either the September or the December operation, they were not eligible to participate in any of the following operations. Additionally, their bid amount in the entry operations was decisive for what they could obtain in any of the following operations (running from March 2015 until March 2016). We therefore consider TLTROs unlikely candidates to impact banks' holdings of sovereign bonds. Another non-standard measure running in parallel to the ECB's PSPP is NIRP. Negative interest rates may induce banks to convert their excess liquidity holdings into (sovereign) bonds. Similar to the TLTRO's, NIRP predates the PSPP starting in June 2014. However, two interest rate cuts lie within our sample period (December 2015 and March 2016, 10bps each) and these two cuts may have affected banks' sovereign bond holdings. Extant literature on the impact of NIRP does not find evidence of banks converting their excess liquidity into sovereign bond holdings (e.g., Demiralp, Eisenschmidt, and Vlassopoulos, 2019). Against this background, NIRP should not confound our results.

B.2. Additional regression designs

Table B.1 presents the baseline regression results including additional balance sheet control variables. In particular, we control for banks' capital share (capital over total assets), their loan book share (loans over total assets), and the share of non-performing loans. The sample size is slightly reduced due to data availability. The results are fully consistent with the baseline results from the paper: The feedback loop between sovereign and bank credit risk is mitigated post-QE and this development is mainly driven by the euro area periphery.

Table B.2 presents additional evidence on the role of the indirect channel of QE on the link between sovereign and bank credit risk. As motivated in our balance sheet model, the indirect channel mainly works through banks' loan portfolio. QE should decrease banks' riskiness through positive effects on economic activity, leading to lower loan loss provision and higher credit demand, contributing to an improvement of the equity position of banks and this should in turn weaken the link between the sovereign and its banks (Altavilla, Boucinha, and Peydró, 2018).

Banks with larger loan portfolio should profit more from this effect. Against this background, we sort the banks according to their loan book shares pre-QE. In particular, we compute the average share of loans over total assets from the first half of 2014. *Top* captures the banks with a share greater than the median. *Bottom* captures the banks with a share lower than the median. Table B.2 shows that the sovereign-bank nexus is mitigated for both groups. However, there is no significant difference in the

reduction of the feedback loop between banks with large and small loan books. This indicates that the indirect channel via loan book shares does not drive our results.

Table B.1: Change in Bank and Sovereign Credit Risk (inlcuding balance sheet controls)

Table B.1 shows the effect of sovereign credit risk on bank credit risk before and after the introduction of the Public Sector Purchase Programme (PSPP). Compared to the baseline results in Table 2, we add balance sheet control variables, which reduces the sample size to 32 banks. Columns (1) and (2) cover the pre-QE period (1 January 2014 to 8 March 2015) and columns (3) and (4) cover the post-QE period (9 March 2015 to 31 December 2016) for all banks in the sample. Column (5) to (8) distinguish between the origin of banks. *Core* captures banks from the core euro area, in particular from Austria, Belgium, Finland, France, Germany, and the Netherlands. *Periphery* includes banks from Greece, Italy, Ireland, Portugal, and Spain. ΔLog(Bank CDS) is the daily change in the natural logarithm of bank CDS. ΔLog(Sovereign CDS) is the daily change in the sovereign CDS of the country in which the bank is headquartered. We add a range of control variables, including bank and day fixed effects, the foreign exposure measure ΔLog(Foreign Exposure CDS), and interactions of bank fixed effects with the change in the CDS market index and the change in the volatility index. t-statistics are in parentheses and the stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	Δ log(Bank CDS)							
	Pre-QE		Post-QE		Pre-QE		Post-QE	
	All	All	All	All	Core	Periphery	Core	Periphery
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Δ log(Sovereign CDS)	0.127	0.111	0.0336	0.0475	0.0366	0.231	0.0110	0.138
	(4.39)	(2.06)	(1.88)	(1.94)	(0.71)	(2.64)	(0.62)	(4.27)
Time/Bank FE	Y/N	Y/Y	Y/N	Y/Y	Y/Y	Y/Y	Y/Y	Y/Y
Foreign Exposure CDS	Y	Y	Y	Y	Y	Y	Y	Y
Bank-level betas	N	Y	N	Y	Y	Y	Y	Y
Balance sheet controls	Y	Y	Y	Y	Y	Y	Y	Y
Observations	9,824	1,413	15,200	5,612	520	893	1,489	4,123
Banks	32	32	32	32	16	16	16	16
R^2	0.230	0.402	0.207	0.388	0.326	0.480	0.528	0.412
Adjusted R^2	0.205	0.281	0.181	0.323	0.187	0.316	0.382	0.329

Table B.2: Change in Bank and Sovereign Credit Risk (pre-QE loan book shares)

Table B.2 shows the effect of sovereign credit risk on bank credit risk before and after the introduction of the Public Sector Purchase Programme (PSPP). The sample with daily frequency covers 21 banks with publicly traded credit default swaps (CDS) from 5 different euro area periphery countries. We sort the banks according to their loan book shares pre-QE. In particular, we compute the average share of loans over total assets from the first half of 2014. *Top* captures the banks with a share greater than the median. *Bottom* captures the banks with a share lower than the median. Columns (1) and (2) cover the pre-QE period (1 January 2014 to 8 March 2015). Columns (3) and (4) cover the post-QE period (9 March 2015 to 31 December 2016). ΔLog(Bank CDS) is the daily change in the natural logarithm of bank CDS. ΔLog(Sovereign CDS) is the daily change in the sovereign CDS of the country in which the bank is headquartered. We add a range of control variables, including bank and day fixed effects, the foreign exposure measure ΔLog(Foreign Exposure CDS), and interactions of bank fixed effects with the change in the CDS market index and the change in the volatility index. t-statistics are in parentheses and the stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	Δ Log(Bank CDS)			
	Pre-QE		Post-QE	
	Top	Bottom	Top	Bottom
	(1)	(2)	(3)	(4)
Δlog(Sovereign CDS)	0.177	0.185	0.0432	0.0367
	(3.09)	(4.28)	(5.55)	(1.34)
Time/Bank FE	Y/Y	Y/Y	Y/Y	Y/Y
Foreign Exposure CDS	Y	Y	Y	Y
Bank-level betas	Y	Y	Y	Y
Balance sheet controls	N	N	N	N
Observations	3,070	3,377	4,630	5,093
Banks	11	10	11	10
R^2	0.321	0.280	0.272	0.362
Adjusted R^2	0.238	0.200	0.186	0.294

Quantitative Easing and the Safe Asset Illusion

Alexander Bechtel, Jens Eisenschmidt, Angelo Ranaldo, and Alexia Ventula Veghazy

Abstract

The massive recourse to Quantitative Easing (QE) calls for a better understanding of its effects on safe assets. Based on a simple balance sheet framework, we show how QE impacts the total amount, cross-sectional distribution, and composition of safe assets in the economy. Analyzing the European Central Bank's (ECB) Public Sector Purchase Programme (PSPP), we find that the amount of universally accessible safe assets decreases and that there is a transfer of safe assets from the non-bank to the banking sector. We call this phenomenon the *safe asset illusion*. The sectoral shift in the holding structure of safe assets has important implications for financial stability and the cost of secured liquidity.

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1. Introduction

Do large-scale asset purchases by central banks—commonly known as Quantitative Easing (QE)—affect the allocation and composition of safe assets in the economy? If so, why and what are the consequences? These are important questions given the enormous and prolonged use of such polices by many central banks around the world. Furthermore, safe assets play an important role for the global financial system and they have been in increasing demand since the financial crisis. (e.g., International Monetary Fund, 2012; Caballero, Farhi, and Gourinchas, 2017; Gorton, 2017).

In this paper, we examine the effect of QE on the total amount, sectoral holdings, and composition of safe assets. We show that even though QE is effectively an exchange of two forms of safe assets—government bonds and central bank reserves—it is not neutral to safe assets, creating a "safe asset illusion". The main friction behind this illusion is the exclusive access to central bank reserves by banks, which creates a class of safe assets that is not *universally accessible*. We start our analysis by deriving conditions for the neutrality of QE in a simple balance sheet framework. Using unique and granular data from the European Central Bank's (ECB) Public Sector Purchase Programme (PSPP), we show that these conditions are violated: The PSPP (1) increases the total amount of safe assets, (2) induces a net-transfer of safe assets from the non-bank to the banking sector, and (3) decreases the amount of universally accessible safe assets. Additionally, we show that the safe asset illusion has distributional consequences for the non-bank sector because non-banks have to pay a safety premium for securely storing their liquidity. Finally, the safe asset illusion also has implications for financial stability because it leads to a deterioration of the collateral quality in money markets creating financial fragility.

What are safe assets? Safe assets are debt contracts that have money-like attributes, which make them attractive as collateral and a store of value (Nagel, 2016). They are information-insensitive in the sense that there is no need for agents to seek information relevant to the instrument's safety (Dang, Gorton, and Holmström, 2015). Due to these attributes, safe assets usually carry a convenience premium (e.g., Krishnamurthy and Vissing-Jorgensen, 2012). Examples of safe assets are highly rated government bonds or central bank reserves. The key characteristic analyzed in this paper is whether a safe asset is *universally accessible*. Some safe assets are only accessible to certain economic agents and financial institutions. For instance, while a government bond is accessible to everyone, many institutional frameworks grant access to central bank reserves (hereafter, reserves) to banks only. Therefore, we define reserves as being not universally accessible. Additionally, we distinguish safe assets from so-called *quasi-safe* assets. Quasi-safe assets behave similarly to safe assets in almost all states of the world. Under these circumstances they provide safety and liquidity benefits and also carry a convenience

premium. In bad states of the world, however, quasi-safe assets become information-sensitive as investors begin having doubts about the true value of these assets (e.g., Moreira and Savov, 2017; Kacperczyk, Perignon, and Vuillemey, 2018). Thus, their convenience yield is wobbling in the sense that their safety and liquidity attributes decrease or disappear (Gorton, 2017). Examples of quasi-safe assets are private debt securities such as certificates of deposits (CDs), bank deposits, mortgage-backed securities (e.g., He and Song, 2020) or public debt securities issued by sovereigns with worse credit ratings.

The contribution of this paper is to examine the effects of QE on safe assets as well as the implications for financial stability and the distribution of wealth in the economy. To this end, we formalize the safe asset illusion in a simple balance sheet framework that enables us to analyze the interactions between the central bank, the non-bank sector, and the banking sector from a safe asset perspective. Based on this framework, we derive conditions for the neutrality of QE to safe assets. In particular, we show that (1) QE is neutral to the total amount of safe assets if the central bank purchases only safe assets (for instance, only safe government bonds), (2) it is neutral to the sectoral holdings of safe assets if the central bank purchases only safe government bonds *and* only from banks, and (3) it is never neutral to the composition of safe assets, that is, to the share of universally accessible safe assets.

In our empirical analysis, we bring the balance sheet framework to data from the ECB in order to test if the neutrality conditions are violated and to what extent they are violated. To this end, we analyze two unique and granular data sets: first, data on PSPP purchases conducted by the ECB between March 2015 and December 2018.[1] Second, we analyze the ECB's Securities Holdings Statistics (SHSS), which contains security-level portfolio holdings of investors resident in the euro area. SHSS data covers the main categories of assets (government and corporate bonds, asset-backed securities and covered bonds) and investors (banks, households, insurance companies and pension funds, other non-financials, and foreign investors).

We find that between Q1 2015 and Q4 2018, the total amount of safe assets in the euro area (EA) increases from 49% to 55% of euro area GDP. Additionally, there is a transfer of safe assets from the non-bank to the banking sector. While the banking sector increases its safe asset holdings as a share of euro area GDP by more than 10.9%, non-banks even reduce their holdings by 4.4%. We also document significant cross-sectional variation in the preference of non-banks to hold safe assets, which leads to cross-sectional differences in how non-banks rebalance their safe asset holdings. The foreign sector is the biggest seller of these assets. Insurance companies and pension funds, on the other hand, even increase their safe asset holdings. Finally, the

[1]To be precise, the PSPP is implemented by the Eurosystem. We use the terms ECB and Eurosystem interchangeably.

share of universally accessible safe assets decreases from 46% of euro area GDP in Q1 2015 to 39% in Q4 2018. Our findings are in line with Koijen et al. (2020), who examine portfolio rebalancing behavior of different sectors during the PSPP until the end of 2017. They look broadly at various asset classes including corporate debt, asset-backed securities, and equity. In contrast, we focus on public debt adding reserves into the mix. In our analysis, we distinguish between safe and quasi-safe assets allowing us to make statements about the effect of QE on the (cross-sectional) distribution and composition of safe assets.

We study two major implications of the safe asset illusion. First, we analyze the impact of the safe asset illusion on the cost of safely storing liquidity. There are two main ways to safely store liquidity: reserves and general collateral (GC) repurchase agreements (repos). While banks can access both, non-banks can only access the latter. As a consequence of the safe asset illusion, non-banks are forced to pay a premium compared to banks if they want to safely store their liquidity. This safe storage premium arising from the segmentation in the market of reserves amounts to 7 – 10 basis points on average. For non-banks, this is a substantial additional cost considering the level of short-term rates. If banks had to pay this premium, their storage cost would have been EUR 3.3 – 4.7 billion higher between March 2015 and December 2018. Second, we examine the implications of the safe asset illusion for financial stability. To this end, we study the role of universally accessible safe assets as collateral. Through its large-scale government bond purchases, the ECB reduces the share of outstanding universally accessible safe assets triggering a substitution in collateralization of safe assets with quasi-safe assets. Consequently, the overall collateral quality in money markets decreases, which leads to financial fragility (Gorton and Ordonez, 2014) or fragile liquidity (Moreira and Savov, 2017).

The safe asset illusion contrasts with the irrelevance paradigm of Wallace (1981), which stipulates that (non-standard) open market operations in assets are irrelevant and do not have any real effect. Woodford (2012) makes use of this paradigm pointing to the fact that targeted asset purchases would not have any effect on prices in a representative agent asset pricing model.[2] There are three strands of the literature that aim to refute these results pointing to channels through which QE might still affect prices: First, according to the signaling channel the accommodative effects of QE originate from the central bank's credible signal to keep rates low for longer periods. QE might influence market participants' views about future monetary policy decisions and the state of the economy. Second, the portfolio rebalancing channel hinges

[2]More specifically, in these models QE is neutral because it involves an exchange of government bonds for reserves leading only to a reshuffle of government assets held by economic agents. These agents ultimately suffer from losses of the central bank because losses lead to higher taxes; hence, it makes no difference whether households hold the bonds directly or via the central bank.

on the imperfect substitutability of assets because they bear specific risk premiums or provide some utility such as liquidity or collateral services (Gertler and Kiyotaki, 2010; Cúrdia and Woodford, 2011). Also, according to preferred-habitat theories investors have a preference for a particular asset or segment of the yield curve (Modigliani, Franco; Sutch, 1966). By altering the amount of assets held in agents' portfolios, QE can then affect asset prices even in the presence of arbitrageurs (Vayanos and Vila, 2021).

Our paper contributes to the third and most recent channel of QE non-neutrality: the reserve channel. This channel centers around the segmentation in the market of central bank reserves. It highlights one key distinguishing characteristic between the purchased government bonds and newly created reserves: Even though both are public liabilities, reserves are issued by central banks and only held by banks; they are not universally accessible. Another important difference is that interest on reserves is a policy variable while interest on bonds is a market variable (Reis, 2017). When central banks buy safe government bonds from banks, QE is neutral from a safe asset perspective as it swaps two safe assets. However, when central banks buy government bonds from non-banks, QE has an unequal impact as non-banks receive the proceeds from selling government bonds in the form of bank deposits exposing them to credit risk in the banking sector. For the non-bank sector, QE is equivalent to a swap of safe assets (government bonds) for quasi-safe assets (bank deposits). Prior research has studied non-neutrality and the effects on inflation (e.g., Benigno and Nisticò, 2017). Christensen and Krogstrup (2019) analyze the portfolio rebalancing effects on banks and non-banks focusing on the reduction of asset portfolio duration. We show that QE induces a redistribution of safe assets from non-banks to banks due to different degrees of accessibility to safe assets. Additionally, we point to the distributional consequences that arise due to a safe storage premium for non-banks. Finally, we show that the safe asset illusion leads to financial fragility by reducing the collateral quality in short-term funding markets.

Our paper contributes to two additional strands of the literature: First, research on safe assets shows that their scarcity leads to global demand and supply imbalances with effects for financial stability and the real economy (e.g, Caballero, Farhi, and Gourinchas, 2008; Caballero and Krishnamurthy, 2009; Barro et al., 2017). It also distinguishes between public/safe and private/quasi-safe assets showing that private safe assets cease to be safe during crises (Sunderam, 2015; Moreira and Savov, 2017; Kacperczyk, Perignon, and Vuillemey, 2018) or that public safe assets crowd out private ones (Azzimonti and Yared, 2018). Our contribution is to show that QE can exacerbate the safe asset scarcity for the non-bank sector as it induces a transfer of these assets from non-banks to banks. In contrast to the existing literature that focuses on the United States, our work analyzes and quantifies safe and quasi-safe assets in the

euro area. Additionally, we show that there is significant heterogeneity in the preference to hold safe assets across different sectors of the economy.

Second, we contribute to the debate about monetary policy as tool for financial stability (e.g., Stein, 2012; Gorton and Ordonez, 2014; Greenwood, Hanson, and Stein, 2016; Moreira and Savov, 2017). As banks issue too many quasi-safe assets (short-term debt) compared to the socially optimal level, Stein (2012) argues that central banks can use their reserves as a tool to mitigate this problem. In the same line of reasoning, Greenwood, Hanson, and Stein (2016) advocate for a more active use of the Federal Reserves's balance sheet to reduce financial risk arising from excessive amounts of maturity transformation. Our results suggest that providing the banking sector with additional liquidity through government bond purchases indeed strengthens the financial stability of banks. However, we also show that this comes at the cost of a reduction of universally accessible safe assets leading to higher general financial fragility (Gorton and Ordonez, 2014) or fragile liquidity (Moreira and Savov, 2017).

The remaining paper is structured as follows: In Section 2, we introduce the concept of safe and quasi-safe assets and present the safe asset illusion in a simple balance sheet framework. In Section 3, we test the predictions from the balance sheet framework using securities holdings data from the ECB. Section 4 examines the distributional consequences of the safe asset illusion for the banking and non-bank sector as well as the implications for financial stability. Finally, in Section 5, we discuss the policy implications of our findings and conclude.

2. The safe asset illusion

2.1 Safe and quasi-safe assets

Safe assets are usually debt contracts that have money-like attributes, which make them attractive as a store of value, tool for liquidity management, and collateral (e.g., Nagel, 2016; Caballero, Farhi, and Gourinchas, 2017; Caballero and Farhi, 2018). Due to these attributes, safe assets usually carry a convenience yield (e.g., Krishnamurthy and Vissing-Jorgensen, 2012; Gorton, 2017). Classical examples are government bonds, such as Treasury bills or Bunds. Safe assets enable economic agents to transact without being exposed to adverse selection. It is inefficient to produce private information about these assets. Therefore, there is no danger that the counterparty has an information advantage, which would create a lemons problem (e.g., Gorton and Pennacchi, 1990; Gorton, 2017). Dang, Gorton, and Holmström (2015) call this characteristic "information sensitivity".

We follow the extant literature and distinguish between safe and quasi-safe assets. Both are information-insensitive during normal times. Safe assets are less prone to information events

than quasi-safe assets because they are not or less exposed to bad news. Additionally, since safe assets are issued by public entities, they are backed by taxation, which makes them inherently more stable and safe (Krishnamurthy and Vissing-Jorgensen, 2015). Therefore, safe assets tend to remain information-insensitive even in times of uncertainty. Quasi-safe assets on the other hand are more prone to becoming information-sensitive. Intuitively speaking, because of the new information, the holders of quasi-safe assets become suspicious about the fundamental value of the underlying debt. They start producing information as soon as the value of information exceeds the cost of producing it. Moreira and Savov (2017) call this situation "fragile liquidity". Fragile liquidity is as good as any other liquidity during quiet times, but it evaporates during times of uncertainty. Gorton and Ordonez (2014) describe the same phenomenon using the term "financial fragility". They show how a small shock to the confidence in safe debt can have large consequences for financial stability at the end of a credit boom. Zou (2019) presents a model in which liquid markets are prone to a self-fulfilling market freeze when buyers suddenly start producing information. This triggers a transition from a liquid to an illiquid state from which there is no equilibrium path back without exogenous intervention. Finally, Kacperczyk, Perignon, and Vuillemey (2018) show that private safe assets cease to be perceived as safe in times of stress. They lose their safety premium.

In this paper, we add one additional dimension to the safe asset taxonomy. We divide (quasi-)safe assets into those that are universally accessible and those that are not. Table 1 summarizes our taxonomy. Differences in the accessibility of safe assets are the main driver behind the safe asset illusion. The classical example for a universally accessible safe asset are government bonds, such as U.S. Treasuries or German Bunds. Reserves on the other hand are safe, but they are not universally accessible.

Examples for universally accessible quasi-safe assets are, among others, government bonds with a low credit rating, mortgage-backed securities, or corporate bonds. Consequently, safe assets are always issued by the public sector, but not all public debt is safe. Finally, quasi-safe assets that are not universally accessible might include investment vehicles such as closed-end funds with a very good credit rating. In this paper, we focus on safe assets, that is, on the first column of Table 1. In Section 3, we operationalize our defintion of safe assets and outline which assets fall into which category.

2.2 Balance sheet framework

In this section, we offer a formal presentation of the safe asset illusion. We develop a simple balance sheet framework to show how QE affects the (1) total amount, (2) sectoral holdings,

Table 1: Safe and quasi-safe assets

	Safe Asset	Quasi-safe asset
Universally accessible	High-quality public debt (e.g., government bonds)	Low-quality public debt and high-quality private debt (e.g, MBS or bank deposits)
Not universally accessible	Central bank reserves	Exclusive and high-quality private investment vehicles (e.g., closed-end funds)

and (3) composition of safe assets.[3] Arguably, similar effects may arise from conventional or other unconventional monetary policy measures such as open market operations and (long-term) refinancing operations. However, there are still several difference: QE is typically at least an order of magnitude larger than open market operations or conventional refinancing operations. Additionally, it targets the core set of safe assets in the economy and it is an outright purchase of these assets instead of "only" a repo, like the ECB's long-term refinancing operations.

Our economy consists of three sectors: the central bank, a banking sector, and a non-bank sector. The distinguishing feature between a bank and non-bank is the access to the balance sheet of the central bank. Hence, what we mean by a bank is any institution with an account at the central bank. This might include entities without a banking license. In the U.S., for instance, some government-sponsored enterprises and money market funds have access to the Federal Reserve. Similarly, we define non-banks as institutions that do not have access to the balance sheet of the central bank. This includes households, non-financial corporations, insurance companies, money market funds (in the euro area), hedge funds, pension funds, etc. In particular, also foreign banks fall into that category.

There are three assets: government bonds G, reserves R, and bank deposits D. Government bonds are in positive net supply, which is exogenous:[4]

$$G = G_{CB} + G_{BA} + G_{NB}, \tag{1}$$

where G_{CB}, G_{BA}, G_{NB} are the government bond holdings of the central bank, banking sector, and non-bank sector, respectively. The other assets are in zero net supply, meaning they are a liability of one of the sectors in our economy. In line with our definition in Section 2.1, we cat-

[3]Recall, that "composition of safe assets" stands for the share of universally accessible and non-accessible safe assets.

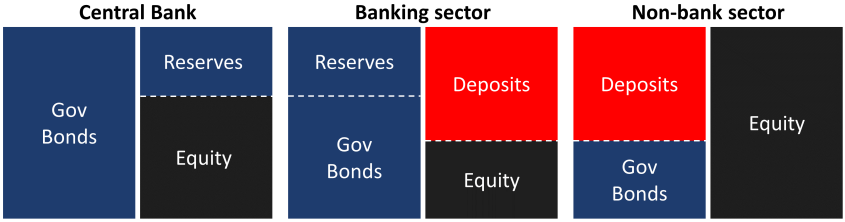
[4]Note, that in the classical macro literature, the central bank and the government are usually one and the same. In our case, it makes sense to distinguish between the two because—at least in the short run—the central bank's decision to purchase government bonds is unrelated to the government's decision to increase or decrease its debt level.

egorize central bank reserves as safe assets and bank deposits as quasi-safe assets. Government bonds can be safe or quasi-safe. We assume the fraction ρ of government bonds to be safe and $(1-\rho)$ to be quasi-safe.

Figure 1 presents stylized balance sheets of our sectors. As government bonds are in positive net supply, they are held as an asset by all three sectors. The central bank issues reserves, which can only be held by the banking sector. The banking sector issues unsecured deposits that are held by the non-bank sector.

Figure 1: Sectoral balance sheets

Figure 1 shows the balance sheet of the central bank, the banking sector, and the non-bank sector.



The balance sheets of the central bank, banking sector, and non-bank sector can be written as:

$$\text{CB}: \quad G_{CB} = R + E_{CB}, \tag{2}$$

$$\text{BA}: \quad G_{BA} + R = D + E_{BA} \tag{3}$$

$$\text{NB}: \quad G_{NB} + D = E_{NB}. \tag{4}$$

Based on this framework, we examine the effects of large-scale government bond purchases by the central bank on the holdings of safe and quasi-safe assets across the different sectors.

Figure 2 illustrates the impact of QE on the sectoral balance sheets. The central bank purchases government bonds from the banking and non-bank sector in the secondary market against reserves, that is, $\Delta R = \Delta G_{CB}$. For simplicity, we assume that the total amount of government debt G is unaffected by these purchases, that is, $\Delta G = 0$. Consequently, the increase in bond holdings at the central bank has to be offset by a decrease in the holdings of the banking and/or non-bank sector. We assume that a fraction γ of the purchased bonds comes from the banking sector and $1-\gamma$ from the non-bank sector. The variable γ is a reduced-form

parameter that reflects the preferences of banks and non-banks to hold government bonds.[5] Using the budget constraint, Equation (1), we can write: $\Delta R = \gamma \Delta G_{CB} + (1-\gamma)\Delta G_{CB}$.

Figure 2: Sectoral balance sheets during QE

Figure 2 shows how the balance sheets of the central bank, the banking sector, and the non-bank sector are affected through government bond purchases by the central bank.

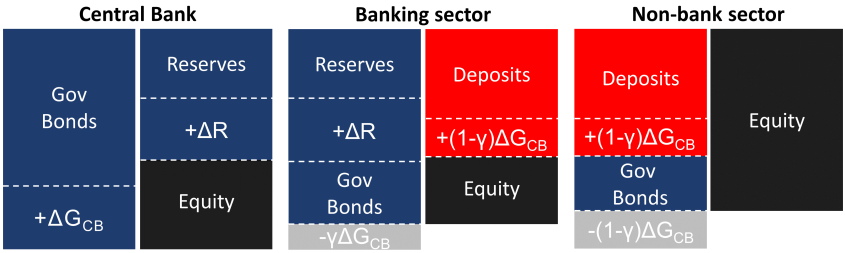


Figure 2 highlights several interesting facts: First, the central bank extends its balance sheet by purchasing ΔG_{CB} government bonds using newly created reserves ΔR. Second, the banking sector receives 100% of the newly created reserves. Hence, for any $\gamma < 1$, the balance sheet of the banking sector increases as a consequence of QE. Third, the non-bank sector sells $(1-\gamma)\Delta G_{CB}$ government bonds through the banking sector, which acts as intermediary. In return, non-banks receive bank deposits such that the size of the balance sheet of the non-bank sector remains constant. Lastly, the banking sector's role as intermediary has two interesting implications: (i) The increase in bank deposits is exogenous to banks. More precisely, the banking sector has to increase the amount of deposits if non-banks decide to sell government bonds to the central bank. (ii) Similarly, the amount of reserves in the banking sector is at least partially exogenous. The sector as a whole cannot avoid holding reserves as long as non-banks sell government bonds to the central bank. The extent to which the non-bank sector sells government bonds—and hence the extent to which both deposits and reserves increase—is determined by $(1-\gamma)$, i.e, the preference of non-banks to hold government bonds. In our empirical analysis we will estimate this parameter for euro area non-banks.

Table 2 summarizes the impact of QE on the total and sectoral holdings as well as the composition of safe assets. Derivations can be found in Section C.1.1. The banking sector sells $\rho\gamma\Delta G_{CB}$ government bonds and receives $\Delta R = \Delta G_{CB}$ reserves in return. The non-bank sector

[5] The term preference should be taken in a broad sense. It encompasses the willingness but also the requirement to hold safe assets; for example, laws and regulations might prescribe to invest a certain amount in government bonds.

sells $\rho(1-\gamma)\Delta G_{CB}$ government bonds and receives only quasi-safe assets in return because it is compensated in the form of bank deposits. Hence, there is a transfer of safe assets from the non-bank to the banking sector.[6] The change in the total amount of safe assets is $(1-\rho)\Delta G_{CB}$. Consequently, the central bank can determine the total amount of safe assets by setting ρ, but it cannot directly steer the sectoral holdings of safe assets because sectoral holdings (also) depend on the preferences of banks and non-banks to hold safe assets, γ. Finally, the first column of Table 2 shows that the change in the total amount of safe assets is composed of an increase in non-universally accessible safe assets and a decrease in universally accessible safe assets. The former increase by $\Delta R = \Delta G_{CB}$ and the latter decrease by $\rho\Delta G_{CB}$.

Table 2 also presents the changes of the total and sectoral holdings of quasi-safe asset. The holdings of the banking sector decrease by $(1-\rho)\gamma\Delta G_{CB}$, that is, the amount of quasi-safe government bonds sold by banks. In case of the non-bank sector, the quasi-safe asset holdings increase by $\rho(1-\gamma)\Delta G_{CB}$, that is, the amount of safe government bonds sold. This is due to the fact that non-banks only receive bank deposits when selling safe government bonds. Additionally, the quasi-safe asset holdings of non-banks do not change if they sell quasi-safe government bonds because such a transaction would simply be a swap of two quasi-safe assets (quasi-safe government bonds against bank deposits). In sum, whether the total amount of quasi-safe assets increases or decreases depends on the relative size of the policy parameter ρ that is determined by the central bank and the preference parameter γ that differs across economic agents.[7] The more safe assets are purchased by the central bank (high ρ) and from the non-bank sector (small γ), the higher the increase of quasi-safe assets.

Table 2: Change in total and sectoral holdings of (quasi-)safe assets

Table 2 presents the changes in total and sectoral holdings of safe and quasi-safe assets. Derivations can be found in the Appendix.

	Safe assets	Quasi-safe assets
Banking sector	$(1-\rho\gamma)\Delta G_{CB}$	$-(1-\rho)\gamma\Delta G_{CB}$
Non-bank sector	$-\rho(1-\gamma)\Delta G_{CB}$	$\rho(1-\gamma)\Delta G_{CB}$
Total	$(1-\rho)\Delta G_{CB}$	$(\rho-\gamma)\Delta G_{CB}$

In order to derive a measure for the preference of different sectors s to hold government

[6] To keep the discussion simple, we abstract from possible government guarantees on bank deposits. The general SAI mechanism remains essentially the same.

[7] In the euro area, ρ is determined by the ECB capital key of the individual member countries.

bonds, we introduce γ^s, where $s \in \{\text{Bank, ICPF, OFI, HH, Other, Foreign}\}$ and $\sum_s \gamma^s = 1$.[8] Against this background, we use

$$\frac{\Delta G^s_{safe}}{G^s_{safe}} = -\frac{\rho \gamma^s \Delta G_{CB}}{G^s_{safe}} \tag{5}$$

as a measure for the cross-sectional variation in the preference to hold safe government bonds. We can do this because the only driver of cross-sectional variation in this measure is variation in γ^s. When bringing this measure to the data, we still need to correct for the fact that the amount of outstanding government bonds also changes due to the issuance of new bonds. We derive this measure in an extension of the framework in the Appendix. While adding the issuance of new government bonds to the framework is necessary to make it fully transparent how our measure can be brought to SHSS data, nothing changes from a conceptual point of view. Since the extension adds some complexity without changing the overall picture, we decided to move it to the appendix.

We can now use the results presented in Table 2 to derive conditions for the neutrality of QE for (1) the total amount, (2) the sectoral holdings, and (3) the composition of safe assets.

Proposition 1 (Safe asset neutrality of QE)

(i) *QE is neutral to the total amount of safe assets if $\rho = 1$, i.e., if the central bank purchases only safe government bonds.*

(ii) *QE is neutral to the sectoral holdings of safe assets if $\rho = \gamma = 1$, i.e., if the central bank purchases only safe government bonds and only from banks.*

(iii) *QE is never neutral to the composition of safe assets, i.e., to the share of universally accessible and non-accessible safe asset.*

First, the central bank can steer the total amount of safe assets in the economy by specifying a particular value for ρ. In particular, if the central bank wants to stay safe asset-neutral, it can set the value of ρ to one and hence purchase only safe government bonds. In this case, QE boils down to a swap of two forms of safe assets: safe government bonds and reserves. Second, the neutrality of QE for sectoral holdings depends on the (relative) preference of the banking and non-bank sector to hold safe government bonds. Neutrality is guaranteed if $\rho = \gamma = 1$, that is, if the central bank purchases only safe assets and only from banks, for example, when only banks

[8] Insurance companies and pension funds (ICPF), other financial institutions (OFI), households (HH), others (Other), and foreign institutions (Foreign) are the non-bank sectors in our data, which we introduce in more detail in Section 3.

are willing to sell these assets. In this case, the balance sheet of the non-bank sector remains unchanged and the banking sector swaps one safe asset (safe government bonds) for another (central bank reserves). Third, QE can never be neutral to the composition of safe assets. The central bank always exchanges reserves for government bonds and hence a non-universally accessible safe asset for one that is universally accessible.

In a nutshell, the policy parameter ρ and preference parameter γ jointly determine the change in total and sectoral safe asset holdings. The central bank can affect the total amount of safe assets in the economy by setting ρ. However, the amount of quasi-safe assets and in particular the sectoral distribution of safe assets are (also) determined by γ, that is, the banking and non-bank sector's preferences to hold government bonds. Consequently, knowing γ is important for the central bank in order to assess the implications of its QE program for the sectoral holdings of safe assets. In the Appendix, we discuss several boundary cases for ρ and γ.

3. Empirical analysis

In this section, we bring our balance sheet framework to data from the euro area in order to examine the (non-)neutrality of the PSPP for safe assets and quantify the effects. We measure changes in total and sectoral holdings of safe assets as well as their composition between March 2015 and December 2018.

3.1 Public Sector Purchase Programme

The PSPP was formally announced in January 2015 and further implementation details were communicated in March 2015, which marks also the start date of the large scale asset purchase program of the euro area. The policy rationale of the PSPP was to provide additional monetary policy accommodation in a situation in which policy rates could not be cut (much) further (the deposit facility rate had reached a level of -0.20 percent and the main refinancing rate stood at 0 percent).

The initial monthly envelope of PSPP purchases was EUR 60 billion, which was increased in April 2016 to EUR 80 billion and then decreased again to EUR 60 billion in April 2017. Between March 2015 and December 2018, the Eurosystem has purchased EUR 2.2 trillion of euro area government bonds, agency bonds and euro area supras (e.g., EIB bonds).[9] The purchase volumes were split according to the capital key. In other words, each national central

[9]Cumulative net purchase figures in this sub-section represent the difference between the acquisition cost of all purchase operations and the redeemed nominal amounts.

bank of the Eurosystem purchased the share of the monthly PSPP envelope that corresponds to its capital share, exclusively focusing on the govenment bonds of their own country.

As of 31 December 2018, out of the total PSPP purchase volume, the Eurosystem had acquired EUR 519 billion in German, EUR 420 billion in French, EUR 365 billion in Italian, EUR 261 billion in Spanish and EUR 115 billion in Dutch public sector bonds, corresponding to 26.1%, 18.3%, 16.9%, 21.8%, 24.5% of all outstanding bonds of these countries.

3.2 Data description

We use data from the Securities Holdings Statistics by Sector (SHSS) database which provides information on holdings of securities by euro area resident sectors. In our sample, debt securities are identified by a unique International Securities Identifier Number (ISIN) and the total reported holdings of these securities per quarter are approximately EUR 19 trillion in nominal value. We merge the SHSS data with the nominal value of the asset purchase programme (APP) holdings of the Eurosystem at the security level and quarterly frequency, amounting to a total of around EUR 2.4 trillion in Q4 2018. In addition, we enrich the database with security level characteristics and outstanding amounts from the Centralised Securities Database (CSDB), and complement the CSDB data with data on credit ratings given by DBRS, Fitch, Moody's and Standard and Poor's. When no sovereign- and ISIN-level credit ratings are available, we use issuer-level credit ratings based on characteristics of the ISINs. Our sample spans from Q2 2014 until Q4 2018.

Following Koijen et al. (2020), we group the SHSS holdings sectors into five euro area sectors: monetary financial institutions (MFI, or: banks), insurance corporations and pensions funds (ICPF), other financial institutions (OFI) which includes money market funds, investment funds and other financial corporations, households (HH), and government and non-financial corporations (Other). We also add the Eurosystem sector characterised by the APP holdings. Finally we create the foreign sector (Foreign)—that is, non-euro area investors—as the residual obtained from the difference between the total outstanding amount of a given security and the aggregate holdings of the corresponding security by euro area sectors.[10] In addition, as CSDB should cover the full universe of euro-denominated securities issued by euro area entities, we assign the total outstanding amount of those securities of interest not included in the SHSS to

[10] A shortcoming of the SHSS data is the difficulty of measuring securities positions of investors located outside the euro area—also known as custodial bias—as foreign holdings are reported to a large extent indirectly via euro area custodians which may then not pick up the country of the final investor. Thus, holdings by the foreign sector are treated as a residual category to match the aggregate outstanding nominal amount of the securities of interest.

the foreign sector.

We distinguish the assets covered in our sample between both government and corporate bonds, asset-backed securities and covered bonds. For the purpose of our analysis, we focus on euro-denominated government debt securities issued by euro area legal entities, including agency bonds and supras held under the PSPP. To this end, we use the CSDB characteristics to filter out securities that are still alive in the investors' holdings portfolio and classify them according to their debt type.[11] Thus, total nominal holdings of government debt securities amount to approximately EUR 8.3 trillion on average over our review period. In addition, holdings by the Eurosystem sector only comprise the PSPP purchases.

3.3 Measuring safe asset volumes

Before we are able to quantify the change in the composition of safe assets in the euro area, we need to operationalize our definition of safe assets. The first requirement for an asset to be universally safe is that it is issued or backed by the government. This excludes private debt. But even in the case of public debt there exists significant heterogeneity in the cross-section of safety and we cannot classify 100% of euro area public debt as safe. Instead, we use sovereign credit ratings to distinguish between safe and quasi-safe public debt. In our baseline definition, we classify public debt issued by sovereigns with at least an AA credit rating as safe; this includes debt from the following countries: Germany, France, the Netherlands, Finland, Austria, Belgium, and Luxembourg.[12] Finally, we define central bank reserves as universally safe.

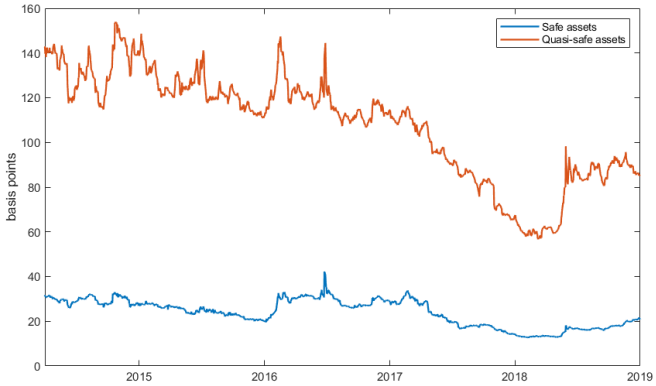
Figure 3 shows the evolution of average CDS spreads over our sample period for EA sovereign bonds falling into either the safe or quasi-safe asset category. The variability of (traded) credit risk is much lower for safe assets than for quasi-safe assets and—in line with the definition of quasi-safeness—there are states of the world during which quasi-safe assets experience significant shocks to their perceived safeness while safe assets remain relatively unaffected.

[11] Securities that have not been redeemed yet, but have a negative residual maturity, can still be reported in the investors' holdings portfolio. We do not include securities with negative residual maturity according to CSDB.

[12] As a robustness check, we examine how our results change if we define only German government bonds as safe.

Figure 3: CDS rates of safe and quasi-safe assets

Figure 3 presents average CDS rates of safe and quasi-safe assets in the euro area.



3.4 Safe asset rebalancing

In order to examine the (non-)neutrality of the PSPP to safe assets, we measure the changes in total and sectoral holdings of safe assets using SHSS data. The first three columns of Table 3 summarize safe asset rebalancing across our sectors from Q1 2015 to Q4 2018. The first column shows the cumulative changes in reserve holdings of the banking sector as a share of euro area GDP. Reserve holdings increases strongly because banks receive reserves irrespective of which sector sells safe and quasi-safe government bonds to the ECB.[13]

The second column summarizes the rebalancing of safe government bonds as a share of euro area GDP. The ECB purchases 11.1% of safe government bonds from the banking and non-bank sector. Banks decrease their holdings by 3.4% and non-banks by 4.4%, leading to a total reduction in safe government bonds of 7.8%. The difference between this reduction and the ECB purchases amounts to 3.3%, which is the positive net issuance of additional safe government bonds by euro area governments as a share of GDP. There is significant variation in rebalancing activity across sectors. The foreign sector is the biggest seller of government bonds, closely

[13]Since the PSPP has not been the only purchase program and since there are other drivers of reserve holdings, the change in reserves deviates from the total PSPP purchase volume (14.3% vs. 16.7% as a share of euro area GDP). Hence, the assumption $\Delta R = \Delta G$ from the balance sheet model does not hold and therefore we use the change in reserve holding ΔR directly to measure the change in safe asset holdings.

followed by banks. Insurance companies and pension funds, on the other hand, even increase their government bond holdings.

The third column presents the relative changes in safe government bond holdings ΔG^s_{safe}, where $s \in \{Bank, ICPF, OFI, HH, Other, Foreign\}$; it serves as our measure of the cross-sectional variation in the preference to hold government bonds. The higher $\frac{\Delta G^s}{G^s}$, the more willing a sector is to hold safe government bonds. In the Appendix, we show that the cross-sectional variation of this measure purely arises from variation in γ and κ, that is, in the preference to hold safe assets (see, Equation (17)). Banks, households, and the foreign sector have the lowest preference to hold safe government bonds.

Table 3: Safe asset rebalancing

Table 3 shows the cumulative rebalancing as a share of euro area real GDP (in percent) from Q1 2015 to Q4 2018 of safe assets (reserves and government bonds rated at least AA), German government bonds, and government bonds rated lower than AA. The third, fifth, and seventh column present relative changes (in percent), which serve as a proxy for the cross-sectional variation in the preference of holing these assets. The top panel reports the rebalancing of the banking and non-bank sector, distinguishing between the five non-bank categories. The second panel reports the rebalancing of the Eurosystem and the bottom panel reports net issuances.

	Safe assets			Gov bonds (DE)		Gov bonds (<AA)	
Sector	$\Delta \frac{R}{GDP}$	$\Delta \frac{G^s}{GDP}$	$\frac{\Delta G^s}{G^s}$	$\Delta \frac{G^s}{GDP}$	$\frac{\Delta G^s}{G^s}$	$\Delta \frac{G^s}{GDP}$	$\frac{\Delta G^s}{G^s}$
Banks	14.33	−3.42	−30.89	−1.31	−32.98	−1.22	−6.95
Non-banks		−4.43	−4.77	−1.59	−5.16	−1.77	−1.92
OFI		−0.07	6.76	−0.10	2.04	−1.11	−14.93
ICPF		0.65	16.46	0.14	21.53	0.88	25.33
HH		−0.12	−39.54	−0.07	−44.18	−0.47	−19.49
Other		−0.07	3.91	0.00	8.68	−0.39	−19.48
Foreign		−4.83	−16.27	−1.56	−10.82	−0.68	−7.07
Eurosystem		11.10		4.01		5.60	
Total	14.33	3.26		1.11		2.61	

The changes in total and sectoral holdings of safe assets are in line with the safe asset illusion. The PSPP is neither neutral to the total amount, nor to sectoral holdings or the composition of safe assets. Panel (a) of Figure 4 plots the holdings of safe assets across different sectors as a share of GDP between July 2014 December 2018. The total amount of safe assets increases from 49% in Q1 2015 to 55% in Q4 2018. This increase is mainly driven by a strong increase in reserve holdings of the banking sector.

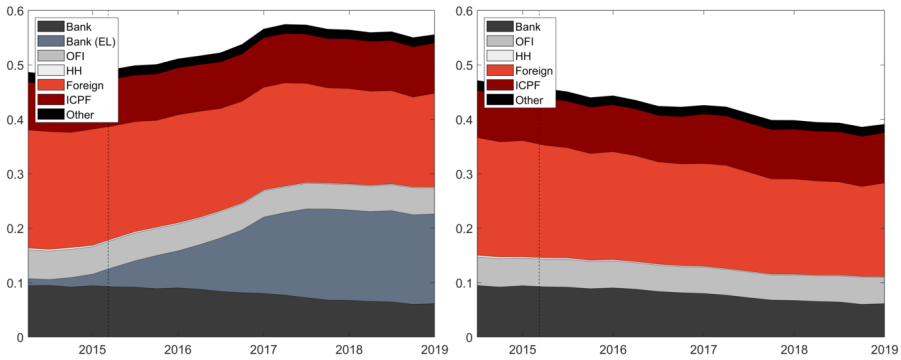
Panel (a) of Figure 4 also shows that the PSPP triggers a change in the cross-sectional

distribution of safe assets: The banking sector increases its holdings of safe assets at the expense of non-banks, in particular the foreign sector. The driver of the increase in the safe asset holdings of the banking sector is the increase in reserve holdings. It more than outweighs banks' decrease of safe government bond holdings because banks do not only receive reserves when selling their own safe government bonds, but also when selling their quasi-safe bonds and when selling bonds for their customers. The holdings of insurance companies and pension funds remain stable. The holdings of households and other non-bank entities are negligible.

Finally, Panel (b) of Figure 4 shows that the PSPP also affects the composition of safe assets. It presents the holdings of universally accessible safe assets. The total amount of these assets decreases from 46% of euro area GDP in Q1 2015 to 39% in Q4 2018. Consequently, the amount of safe assets that are not universally accessible (that is, reserves) increases at the expense of universally accessible safe assets (that is, government bonds).

Figure 4: Safe asset rebalancing

Panel (a) of Figure 4 presents the safe asset holdings of the banking and the different non-bank sectors as a share of GDP. For banks, we distinguish between government bond holdings (dark grey) and reserves (light grey). Reserves are measured as the outstanding amount of excess liquidity (EL), which is defined as the reserve holdings of euro area banks at the ECB above and beyond the minimum reserve requirements. Panel (b) shows the universally accessible safe asset holdings of our sectors.



(a) Safe assets **(b) Universally accessible safe assets**

In particular, the cross-sectional variation in the rebalancing of safe assets is in line with the safe asset illusion. It is not surprising that especially banks, households, and foreign institutions are willing to reduce their safe government bond holdings. In other words—and as shown by the low values for $\frac{\Delta G^s}{G^s}$—these sectors have a lower preference to hold safe government bonds because they have lower opportunity cost of holding these assets: Banks are in an exclusive position because they receive back another type of safe assets—that is, reserves—when sell-

ing government bonds. Households are willing to reduce their safe government bond holdings because the deposit insurance acts as a transformation technology for them, transforming a quasi-safe asset into a safe asset (up to 100,000 EUR, which is a meaningful size for the average household). Finally, the trade-off for the foreign sector is of a somewhat different nature because safe euro area government bonds can be replaced by a similar safe government bond from another jurisdiction—for example, US treasuries—without fundamentally changing the risk profile of the asset.

3.5 Robustness checks

The fourth and fifth column of Table 3 present the rebalancing volumes for German government bonds.[14] These numbers serve as a robustness check to examine if our results change when applying a more restrictive definition of safe assets. The nominal volumes are of course lower when looking only at German government bonds. However, the cross-sectional variation of the preferences to hold safe government bonds—measured by $\frac{\Delta G^s}{G^s}$—is similar to our baseline results. Banks, households, and the foreign sector are most willing to reduce their safe government bond holdings.

The sixth and seventh column of Table 3 present the reblancing volumes for quasi-safe government bonds, that is, bonds rated lower than AA. The cross-sectional variation in the preferences to hold these bonds differs from our baseline results. Except for insurance companies and pension funds, which increase their holdings of quasi-safe bonds, all other sectors reduce their holdings. These results support our approach to measuring safe and quasi-safe assets using AA as a rating threshold. There seems to be a difference in the rebalancing behavior between government bonds with ratings above and below this threshold.

4. Implications of the safe asset illusion

In this section, we discuss two main implications of the safe asset illusion: First, we analyze the premium that non-banks have to pay for safely storing their liquidity. There are two main ways to safely store liquidity: central bank reserves and general collateral (GC) repurchase agreements (repos). While banks can rely on both, non-banks cannot access the central bank deposit facility and therefore they have to pay a premium to ensure that their liquidity is stored safely. Second, we show that the PSPP reduces the collateral quality in the money market, which may adversely impact financial stability.

[14] German government bonds follow the same definition as overall government bonds, including German agency bonds held under the PSPP.

4.1 Distributional consequences for the banking and non-bank sector: safe storage premium

The GC repo market with safe assets as collateral is one of very few—if not the only—possibilities for non-banks to deposit their short-term liquidity nearly without risk.[15] A GC repo is conceptually identical to a (very) short-term secured loan. Hence, the cash-rich agent lends its funds to (or deposits with) a cash-seeking agent at a predefined rate and maturity against collateral.

Since the start of the PSPP, however, the repo rate has fallen strongly, in particular for repos backed by safe assets. Extant literature suggests that large-scale government bond purchases render safe assets scarce, which is reflected in lower rates for these assets in the repo market (e.g., D'Amico, Fan, and Kitsul, 2018; Arrata et al., 2020; Corradin and Maddaloni, 2020). Therefore, it has become more and more expensive to store short-term liquidity safely. For banks, the deposit facility rate (DFR) is a lower bound for the rate they accept to deposit their cash. Hence, if the repo rate drops below the DFR, banks have a strong incentive to deposit their cash at the deposit facility instead of using the repo market. Non-banks on the other hand do not have access to this facility. Their main alternative to a bank deposit is the repo market, which increases their safe storage cost relative to that of banks, creating a safe storage premium. This premium can be interpreted as a convenience yield that originates due to a market segmentation in the market for reserves. The safe asset literature points to two main determinants of the convenience yield: a safety and a liquidity premium (e.g., Krishnamurthy and Vissing-Jorgensen, 2012; Sunderam, 2015; Gorton, 2017), which in turn increases with the opportunity cost of holding money (Nagel, 2016). The segmentation inherent in the monetary policy setting granting the access only to banks induces non-banks to pay a convenience yield for holding liquidity safely.

Figure 5 plots the rate on the ECB's deposit facility together with the overnight rate on euro GC repos backed by safe euro area government bonds (blue) and German government

[15] There are other financial instruments for holding liquid positions such as certificates of deposit and savings or money market accounts. However, (reverse) repos secured by safe assets represent the safest option for lending with very short maturities. The asset being used as collateral can be a particular asset (special collateral or SC repos) or any asset from a predefined basket of assets (general collateral or GC repos). We focus on GC repos because this is the market segment that is used to manage liquidity, while SC repos are rather used to borrow or lend securities.

bonds (black).[16] In an overnight GC repo, the non-bank deposits cash overnight in return for a government bond. The transaction is reversed the next day. Both the DFR and GC repo rate have moved to negative territory already in 2014. Additionally, the repo rate has dropped below the DFR shortly after the start of the PSPP and stayed there ever since. Hence, since at least mid-2015 non-banks have to pay a premium to store their overnight liquidity safely. Between March 2015 and December 2018, this premium has averaged 7 basis points for safe government bonds and 10 basis points for German government bonds.

These costs likely represent a lower bound estimate for the costs of non-banks for a GC repo as these rates are those observed on large platforms which typically do not have non-banks among their customers. Eisenschmidt, Ma, and Zhang (2020) show that non-banks can access the repo market only at significantly higher costs than banks. Looking at repo rates in the OTC segment contained in the ECB's MMSR statistic allows separating repo trades according to their counterparty. Repo spreads paid by non-banks are significantly higher than those paid by banks, with non-banks paying between 10 – 15 basis points higher rates than banks, although the drawback of the approach is that a clean separation between GC and SC repos is not possible and the estimated spread between non-banks and banks may be biased upwards. In any case, the reported premia are substantial given the very low interest rates in the money market. If banks had to store their liquidity in the GC repo market, that is, they would have to pay a similar type of premium as non-banks to safely store their reserves, they would have faced additional cost of EUR 3.3 – 4.7 billion between March 2015 and December 2018.[17] Consequently, the market segmentation in the market for central bank reserves creates a wedge between the banking and non-bank sector when it comes to the costs of safely storing cash.

4.2 Fragile liquidity

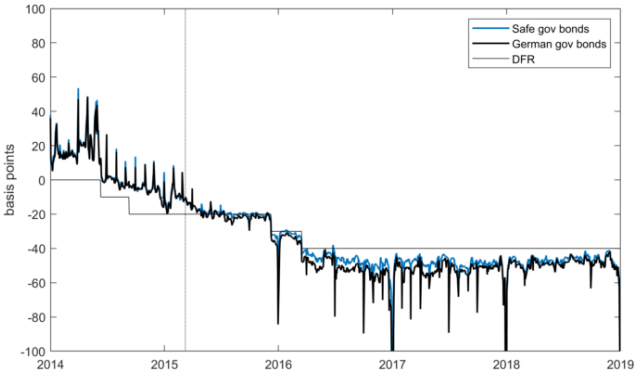
In this section, we show that due to the PSPP, the overall quality of collateral in the money market decreases. The rationale behind this development is straight-forward: With the start

[16] We collect the underlying data from the three major repo exchanges in the euro area: BrokerTec, Eurex, and MTS. For a more detailed description of the market and this dataset, see Ranaldo, Schaffner, and Vasios (2020).

[17] Computed as average amount of excess liquidity times 7 basis points (lower bound) and 10 basis points (upper bound) annualized interest rate spread for the period March 2015 – December 2018. Recall that excess liquidity is defined as the reserve holdings of euro area banks at the ECB above and beyond the minimum reserve requirements.

Figure 5: The safe storage premium

Figure 5 plots the rate on the ECB's deposit facility rate together with the rate on general collateral repurchase agreements backed by safe government bonds (blue) and German government bonds (black). The dotted vertical line marks the start of the PSPP purchases in March 2015.



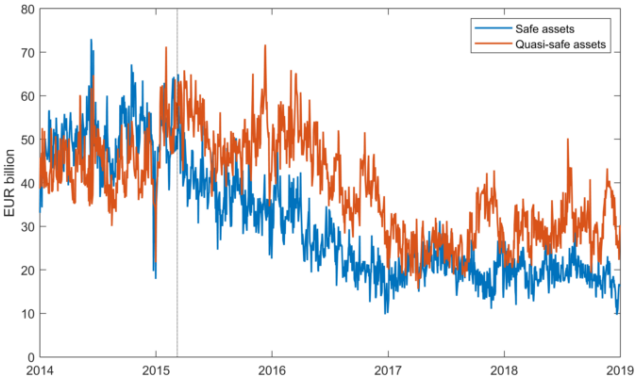
of the PSPP, the share of universally accessible safe assets steadily decreases because the ECB acts as buy and hold investor of safe government bonds. In particular, the ECB purchases more safe than quasi-safe government bonds (in absolut and relative terms). This reduction in the relative supply of safe government bonds is reflected in the use of these assets as collateral in the money market. The consequent substitution from safe to quasi-safe collateral is important because it contributes to financial fragility.

Figure 6 plots the trading volume of overnight euro GC repos traded on the three major exchanges in the euro area (BrokerTec, Eurex, and MTS). The figure distinguishes between repos backed by safe and quasi-safe government bonds. Before the start of the PSPP purchases—indicated by the dotted vertical line—cumulated trading volumes of repos backed by quasi-safe assets were slightly below those backed by safe assets. After the start of the PSPP, repo volumes start to fall because of the additional excess liquidity in the system. However, trading volumes of repos backed by safe assets fall faster than those backed by quasi-safe assets. Thereby the collateral base in the repo market deteriorates, increasing the share of quasi-safe assets.

As discussed above, quasi-safe assets behave similarly to safe assets during normal times and even carry a convenience premium (e.g., Kacperczyk, Perignon, and Vuillemey, 2018). However, their convenience yield is wobbling because in bad times, their safety and liquidity attributes reduce or can even disappear swiftly. The main issue is that quasi-safe assets become information-sensitive as investors doubt the true value and risk of these assets. This mechanism also applies to quasi-safe assets used as collateral impairing their collateral value. Against this

Figure 6: GC repo trading volumes

Figure 6 plots the repo trading volume of overnight euro GC repos collateralized by safe and quasi-safe assets. The data captures repos traded on the three major trading platforms in Europe: BrokerTec, Eurex, and MTS. The dotted vertical line marks the start of the PSPP purchases.



background, a collateral base consisting of a high share of quasi-safe assets leads to financial fragility (Gorton and Ordonez, 2014) or fragile liquidity (Moreira and Savov, 2017).

Table 4 presents summary statistics for the share of safe assets used as collateral in the euro repo market. Pre-PSPP captures the period before the start of the PSPP purchases from 1 January 2014 until 8 March 2015. The average share of safe collateral amounts to 53% during that period. The variation in the share of safe collateral is rather small with only 4.3%. The PSPP period starts on 9 March 2015 and ends on 31 December 2018. The share of safe collateral used in money market transactions decreases significantly after the start of the PSPP. On average it is about 10% lower during the PSPP period than pre-PSPP. At the end of our sample in December 2018, the share of safe collateral is even below 30%.

Table 5 provides additional evidence for the relation between a reduction in the supply of safe government bonds through the PSPP and a decreasing share of safe collateral in the euro GC repo market. It presents the results of the following regression:

$$\begin{aligned} \Delta Safe\ Col\ Share = \alpha + \beta \Delta Safe\ Gov\ Bond\ Share \\ + \gamma_1 \Delta iTraxx_t + \gamma_2 \Delta VSTOXX_t + \gamma_3 \Delta EL_t + \varepsilon_t, \end{aligned} \tag{6}$$

where *Safe Col Share* is the safe collateral share in the euro GC repo market $\left(\frac{Vol_t^{SA}}{Vol_t^{Total}}\right)$, *Safe Gov Bond Share* is the share of outstanding safe euro area government bonds, that is, the share of bonds that is available in the market and not (yet) held by the ECB $\left(\frac{Outstanding_t^{SA}}{Outstanding_t^{Total}}\right)$.

Table 4: Summary statistics for the share of safe collateral

Table 4 presents summary statistics for the share of safe assets used as collateral in the euro repo market. Pre-PSPP captures the period before the start of the PSPP purchases from 1 January 2014 until 8 March 2015. Post-PSPP captures the the period of PSPP purchases, starting on 9 March 2015 and ending on 31 December 2018.

Safe collateral share (%)	Mean	Median	Std	Min	Max	N
Pre-PSPP	52.74	52.80	4.30	35.73	62.71	301
PSPP period	40.41	40.36	6.21	23.55	58.98	977
2015 (after 8 March)	42.91	42.68	4.38	31.08	53.03	210
2016	36.99	36.79	4.85	24.99	50.49	257
2017	42.68	43.35	7.27	23.55	58.98	255
2018	39.51	39.41	5.72	25.63	56.43	255

$iTraxx_t$ is the iTraxx Europe. It captures variation in CDS spreads that might be caused by changes in market-wide credit or liquidity risk. $VSTOXX_t$ captures changes in expectations about aggregate volatility. It reflects the investor sentiment and overall economic uncertainty by measuring the 30-day implied volatility of the EURO STOXX 50. EL_t is the level of excess liquidity holdings. Including EL_t enables us to control for potential changes in the demand for safe collateral that are driven by the need to safely store the additional liquidity from the PSPP. Finally, ε_t is the error term. In order to ensure stationarity and to rule out spurious correlation, we take first differences of all variables. Additionally, we estimate Equation (6) using robust standard errors.

Since GC repo baskets only exist for selected euro area countries, we consider only the following countries in this analysis: Austria, Belgium, Germany, Finland, France, Luxembourg, the Netherlands (safe) and Spain, Greece, Ireland, and Portugal (quasi-safe). In order to control for end-of-quarter effects and eliminate problems stemming from extreme seasonalities common to repo markets, we exclude the last day of each quarter from the regression. Leaving these observations in does not qualitatively change any of the results.

Following the rationale above, a lower share of outstanding safe government bonds should lead to a lower share of safe collateral in the repo market. The first column of Table 5 confirms this hypothesis. If the share of safe government bonds decreases by 1%, the share of safe collateral decreases by about 4%. The second column shows that this result is robust to variation in aggregate measures of credit risk, volatility, and excess liquidity.

Table 5: Fragile liquidity

Table 5 presents the results of regressing the safe collateral share in the euro GC repo market on the share of outstanding safe euro area government bonds—that is, the share of bonds that is available in the market and not (yet) held by the ECB. t-statistics are shown in parentheses. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	(1)	(2)
	Δ Safe Col Share	Δ Safe Col Share
Δ Safe Gov Bond Share	3.953*	3.780*
	(1.79)	(1.70)
Δ iTraxx Europe		0.00939
		(0.10)
Δ VSTOXX		−0.0116
		(−0.08)
Δ Excess Liquidity (EURbn)		7.10e-06
		(0.53)
Constant	−0.00595	−0.0191
	(−0.04)	(−0.13)
N	948	948
R^2	0.00314	0.00346
R^2_{adj}	0.00208	−0.000768

5. Conclusion

We propose a simple balance sheet framework outlining the non-neutrality of large-scale government bond purchases—known as Quantitative Easing, short: QE—to safe assets. We show that while QE increases the total amount of safe assets, it transfers safe assets from the non-bank to the banking sector and it decreases the amount of safe assets that are universally accessible. We call this phenomenon the *safe asset illusion*. In our empirical analysis, we show that during the ECB's Public Sector Purchase Programme—between Q1 2015 and Q4 2018—the total amount of safe assets increases from 49% to 55% of euro area GDP. However, this increase is exclusively driven by newly issued central bank reserves and only the banking sector profits from it. The safe asset holdings of the non-bank sector decrease by 4.4% during the same period. Importantly, the total amount of universally accessible safe assets decreases from 46% of euro area GDP in Q1 2015 to 39% in Q4 2018, contributing significantly to the overall scarcity of safe assets in the euro area. We examine two implications of this safe asset scarcity for the distribution of wealth and financial stability: First, since non-banks do not have access to central bank reserves, they have to pay a premium for safely storing their liquidity. Second, the PSPP

deteriorates the collateral quality in the money market.

The main friction behind the safe asset illusion is the market segmentation originating from granting only the banking sector access to the balance sheet of the central bank. This gives rise to several possible policy responses that can mitigate the adverse effects of the safe asset illusion: First, the ECB could extend the access to its reserves to a wider range of institutions. This would allow (parts of) the non-bank sector to profit from the possibility to safely and (relatively) cheaply store liquidity in the deposit facility (or a similar facility). Against this background, the debate around retail central bank digital currencies (CBDC) seems interesting because a retail CBDC would give all economic agents access to central bank money. Of course, the implications of a retail CBDC go far beyond its effect on safe assets. Nevertheless, it seems worth to include this dimension into the debate surrounding the introduction of a CBDC.

A second policy response to address the adverse effects of the safe asset illusion would be to increase the availability of universally accessible safe assets. For instance, the ECB could intensify its efforts to channel back safe assets into the market via its securities lending facility. Alternatively, it could issue its own safe assets, for instance, in form of ECB Debt Certificates (Hardy, 2020). Securities lending as well as ECB Debt Certificates would mitigate the scarcity of safe collateral in the repo market, leading to higher repo rates. Therefore, these policies could decrease the cost of safely storing liquidity for the institutions without access to the deposit facility.

The goal of this paper was to outline and document the effect of QE—in particular, of the PSPP—on the total amount, sectoral distribution, and composition of safe assets. Our findings raise a couple of interesting questions, which can be addressed by future research. For instance: Are banks profiting or suffering from the additional safe asset holdings? Since excess liquidity is remunerated at negative interest rates, it is open whether the net effect of additional safe assets is positive or negative for the banking sector. Moreover, the safe asset illusion suggests that the cross-sectional heterogeneity in the preferences to hold safe government bonds have important implications for the transmission efficiency of QE. Especially those sectors with high opportunity cost of holding safe assets are less willing to give these assets away. Against this background, it seems likely that the ex ante holding structure of government bonds matters for the efficiency of QE. If most of the government bonds are in the hands of sectors with a high preference to hold government bonds, the price impact of asset purchases might increase.

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Appendix C.

C.1. Balance sheet framework

C.1.1 Derivation of results in Table 2

Overall, the sectoral holdings of safe and quasi-safe asset holdings of the banking and non-bank sector change as follows (recall that $\Delta R = \Delta G_{CB}$):

$$\Delta SA_{BA} = (1 - \rho\gamma)\Delta G_{CB} \tag{7}$$
$$\Delta SA_{BA}^{Quasi} = -(1 - \rho)\gamma\Delta G_{CB} \tag{8}$$
$$\Delta SA_{NB} = -\rho(1 - \gamma)\Delta G_{CB} \tag{9}$$
$$\Delta SA_{NB}^{Quasi} = \rho(1 - \gamma)\Delta G_{CB}, \tag{10}$$

which leads to a total change in safe and quasi-safe asset supply of:

$$\Delta SA = \Delta SA_{BA} + \Delta SA_{NB} \tag{11}$$
$$= (1 - \rho\gamma)\Delta G_{CB} - \rho(1 - \gamma)\Delta G_{CB} \tag{12}$$
$$= (1 - \rho)\Delta G_{CB} \tag{13}$$
$$\Delta SA^{Quasi} = \Delta SA_{BA}^{Quasi} + \Delta SA_{NB}^{Quasi} \tag{14}$$
$$= -(1 - \rho)\gamma\Delta G_{CB} + \rho(1 - \gamma)\Delta G_{CB} \tag{15}$$
$$= (\rho - \gamma)\Delta G_{CB}, \tag{16}$$

where ρ is the fraction of safe government bonds and γ the fraction of government bonds purchased from the banking sector.

C.1.2 Boundary cases for ρ and γ

It is useful to discuss several boundary cases for ρ and γ.

$\underline{\rho = \gamma = 1}$: The central bank purchases only safe assets and only from banks, meaning only banks are willing to sell these assets. In this case, (1) the total amount of safe and quasi-safe assets remains unchanged. QE is a swap of two forms of safe assets (government bonds vs. reserves). Since this swap takes place within the banking sector, (2) also the sectoral holdings of safe assets do not change. Nevertheless, (3) the composition of safe assets changes because government bonds are universally accessible while reserves are not. Universally accessible safe assets are substitute one for one with non-universally accessible safe assets.

$\underline{\rho = 1 \ \& \ \gamma = 0}$: The central bank purchases only safe assets and only from non-banks, meaning only non-banks are willing to sell these assets. In this case, (1) the total amount of safe assets remains unchanged. However, contrary to the first case, the amount of quasi-safe assets increases exactly by the amount of the government bond purchases. Additionally, (2) the sectoral holdings of safe and quasi-safe assets change. The increase in safe asset holdings of banks is offset by a loss in safe asset holdings of non-banks. Hence, there is a transfer of safe assets from banks to non-banks due to the market segmentation in the market for reserves. Instead of being compensated with safe assets, non-banks receive bank

deposits (quasi-safe assets) when selling their safe government bonds. Finally, (3) universally accessible safe assets are substitute one for one with non-universally accessible safe assets.

$\underline{\rho = 0 \ \& \ \gamma = 1:}$ The central bank purchases only quasi-safe assets and only from banks. In this casse, (1) the total amount of safe assets increases and the the amount of quasi-safe assets decreases by the same amount. Since these transaction take place on the balance sheet of the banking sector, (2) the (quasi-)safe asset holdings of non-banks remain unchanged. (3) The amount of universally accessible safe assets remains unchanged because the central bank purchases only quasi-safe assets. Simultaneously, the amount of non-universally accessible safe assets increases because the central bank pays its purchases with newly creates reserves.

$\underline{\rho = 0 \ \& \ \gamma = 0:}$ The central bank purchases only quasi-safe assets and only from non-banks. In this case, (1) the total amount of safe assets increases and the amount of quasi-safe assets remains unchanged. The former is due to the fact that banks receive safe reserves because they act as intermediary. Hence, (2) the safe asset holdings of the banking sector increase. The latter is due to the fact that non-banks are compensated with bank deposits. They swap two forms of quasi-safe assets such that their (quasi-)safe asset holdings remain unchanged. (3) The amount of universally accessible safe assets remains unchanged because the central bank purchases only quasi-safe assets. Simultaneously, the amount of non-universally accessible safe assets increases because the central bank pays its purchases with newly creates reserves.

C.2. Balance sheet framework extension: positive net issuance of new government bonds

The net issuance of government bonds is an important driver of changes in total and sectoral holdings of government bonds. Against this background, we extend our framework. We assume that an exogenous treasury can change the net debt level by purchasing or selling government bonds.[18] Contrary to central bank purchases, these operations change the amount of outstanding government bonds, that is, $\Delta G \neq 0$. Since governments usually increase their net debt levels, we consider the case in which the treasury sells bonds, that is, $\Delta G > 0$. We assume it sells a fraction κ to the banking and $(1-\kappa)$ to the non-bank sector. Additionally, we introduce the parameters $[\rho_1, \rho_2]$ to distinguish between safe and quasi-safe government bonds; ρ_1 represent the amount of safe assets purchased by the central bank as a share of total purchases and ρ_2 represents the amount of safe assets issued by the treasury as a share of total net issuance.

Table C.1 presents the change in total and sectoral holdings of (quasi-)safe assets, if we allow for changes in government debt levels. Derivations can be found in the Appendix. Since the banking sector acts as an intermediary for non-banks, it receives additional reserves whenever banks or non-banks sell government bonds to the central bank. Hence, reserve holdings increase by ΔG_{CB}. Similarly, the banking sector spends reserves whenever banks or non-banks purchase newly issued government bonds. Hence, the reserve holdings decrease by ΔG. To arrive at the total change in safe asset holdings of the banking sector, we still need to take into account that banks sell safe government bonds to the central bank. This reduces their safe asset holdings by $\rho_1 \gamma$. Additionally, they purchase safe newly issued government

[18] Note, that selling (purchasing) government bonds corresponds to the situation in which the amount of newly issued government bonds exceeds (is smaller than) the amount of maturing ones, such that the net indebtedness of the government increases (decreases).

bonds. This increases their safe asset holdings by $\rho_2\kappa\Delta G$. Taken together, the total change in safe asset holdings of the banking sector amounts to $(1-\rho_1\gamma)\Delta G_{CB} - (1-\rho_2\kappa)\Delta G$.

The banking sector reduces its quasi-safe asset holdings by $(1-\rho_1)\gamma\Delta G_{CB}$ because it sells quasi-safe government bonds to the central bank. Simultaneously, it increases its quasi-safe asset holdings by $(1-\rho_2)\kappa\Delta G$ because it purchases quasi-safe government bonds from the government.

Table C.1: Change in total and sectoral holdings of (quasi-)safe assets (extension)

Table C.1 presents the changes in total and sectoral holdings of safe and quasi-safe assets.

	Safe assets	Quasi-safe assets
Banking sector	$(1-\rho_1\gamma)\Delta G_{CB} - (1-\rho_2\kappa)\Delta G$	$-(1-\rho_1)\gamma\Delta G_{CB} + (1-\rho_2)\kappa\Delta G$
Non-bank sector	$-\rho_1(1-\gamma)\Delta G_{CB} + \rho_2(1-\kappa)\Delta G$	$\rho_1(1-\gamma)\Delta G_{CB} - \rho_2(1-\kappa)\Delta G$
Total	$(1-\rho_1)\Delta G_{CB} - (1-\rho_2)\Delta G$	$(\rho_1-\gamma)\Delta G_{CB} - (\rho_2-\kappa)\Delta G$

The non-bank sector reduces its holdings of safe government bonds by $\rho_1(1-\gamma)\Delta G_{CB}$ because it sells these bonds to the central bank. Simultaneously, it increases its holdings of safe government bonds by $\rho_2(1-\kappa)\Delta G$ because it purchases these bonds from the government. Additionally, the non-bank sector increases its quasi-safe asset holdings by $\rho_1(1-\gamma)\Delta G_{CB}$ because it receives bank deposits for selling safe government bonds to the central bank. And it decreases its quasi-safe asset holdings by $\rho_2(1-\kappa)\Delta G$ because it uses its bank deposits to purchase safe government bonds from the government.

The extent to which total and sectoral holdings of (quasi-)safe assets change depends on the parameters ρ_1, ρ_2, γ, and κ. Note that only ρ_1 can be determined by the central bank. All other parameters are outside the control of monetary policy and are either determined by the government (ρ_2) or by market participants (γ and κ). The bottom line of Table C.1 shows that the central bank and the government can together control the total amount of safe assets. However, they cannot directly impact the cross-sectional distribution because this (also) depends on γ and κ, that is, on the preference of banks and non-banks to hold government bonds. It seems likely that γ and κ are not independent because (non-)banks can achieve their preferred level of safe asset holdings by adjusting the amount of government bonds they sell to the central bank (γ) and/or the amount they purchase in primary auctions (κ).

Against this background, we derive a measure for the preference to hold safe government bonds as a function of γ and κ, which we can later bring to the data. To this end, we define define $\gamma = \gamma_{Bank}$ and $(1-\gamma) = \gamma_{Non-bank} = \gamma_{ICPF} + \gamma_{OFI} + \gamma_{HH} + \gamma_{Other} + \gamma_{Foreign}$. We do the same for κ. Using SHSSdata, we are able to measure the change in safe government bond holdings of our sectors ΔG^s_{safe}, where $s \in \{Bank, ICPF, OFI, HH, Other, Foreign\}$. Against this background, we use

$$\frac{\Delta G^s_{safe}}{G^s_{safe}} = -\frac{(\rho_1\gamma^s\Delta G_{CB} + \rho_2\kappa^s\Delta G)}{G^s_{safe}} \tag{17}$$

as a measure for the cross-sectional variation in the preference to hold safe government bonds. We can do this because the only driver of cross-sectional variation in this measure is variation in γ and κ.

Finally, we can use the results presented in Table C.1 to derive conditions for the neutrality of QE when allowing the total amount of outstanding government bonds G to change. As in *Proposition 1*, we can derive these conditions for (1) the total amount, (2) the sectoral holdings, and (3) the composition

of safe assets.

Proposition 2 (Safe asset neutrality of QE)

(i) *QE is neutral to the total amount of safe assets if*

- $\rho_1 = \rho_2 = 1$*, i.e., if the central bank purchases only safe government bonds and only safe government bonds are issued*
- $\rho_1 \Delta G_{CB} = \rho_2 \Delta G$*, i.e., the amount of safe government bonds purchased by the central bank equals the amount of newly issued safe government bonds*

(ii) *QE is neutral to the sectoral holdings of safe assets if*

- $\rho_1 = \rho_2 = \gamma = \kappa = 1$*, i.e., if the central bank purchases only safe government bonds and only from banks; and if only safe government bonds are issued and only to banks*
- $\Delta G_{CB} = \Delta G$ *&* $\rho_1 = \rho_2$ *&* $\gamma = \kappa$*, i.e., the amount of government bonds purchased by the central bank equals the amount of newly issued government bonds, the share of safe government bonds purchased by the central bank equals the share of safe government bonds in primary auctions, and the share of bonds purchased from banks equals the share issued to banks*

(iii) *QE is never neutral to the composition of safe assets, i.e., to the share of universally accessible and non-accessible safe asset.*

C.3. Data characteristics

The SHSS data vintage used for our sample refers to June 2020 and data is collected on a quarterly basis by euro-area custodians. Sectors in the SHSS database are defined according to the ESA 2010 classification. Securities held exclusively by non-euro area sectors that are not held via a euro area custodians are not available in SHSS and, thereafter, neither their amount outstanding. In addition, securities which have not been redeemed yet, but have a negative residual maturity can still be reported in the investors' holdings portfolio. Thus we do not include securities with negative residual maturity according to CSDB. We define government bonds as securities issued by ESA 2010 sectors S_13, S_1311, S_1312, S_1313 and S_1314 (general, central and local government and social security). The classifications of the CSDB debt type variable changes after 2016Q3. Up to 2016Q3, we define corporate bonds as debt types D.1, D.11, D.15, D.16, D.164, D.18, D.3 and D.32 and which are not issued by the government sector, as well as securities included in the ECB's Corporate sector purchase program. Covered bonds and asset-back securities correspond to debt types D.21, D.23 and D.233 which are not issued by the government sector, as well as to securities included in the ECB's asset-backed securities purchase program and covered bond purchase program 3. After 2016Q3, we still follow the securities' classification according to the inclusion into the corresponding ECB's purchase programs, but we define corporate bonds as debt types D.1, D.11, D.14, D.141, D.15, D.16, D.18, D. 181, D.1811, D.1812, D.1813, D.1819, D.182, D.1821 and D.1822 and which are not issued by the government sector; and covered bonds and asset-back securities correspond to debt types D.13, D.131 and D.139 and not issued by the government sector.

Collateral is King: Quantitative Easing and the Repo Scarcity Premium

Alexander Bechtel

Abstract

We provide a new explanation for the interaction between Quantitative Easing (QE) and short-term interest rates. Since the onset of the Public Sector Purchase Programme (PSPP) in the euro area in March 2015, short-term interest rates began to diverge and partially fell below the European Central Bank's (ECB) deposit facility rate. We show that these interest rate movements are driven by a joint supply and demand shock creating a *scarcity premium* for money market rates backed by high-quality collateral. Purchasing 1% of the outstanding government bonds is associated with a 1.0−1.7 basis points increase of the scarcity premium because the supply of collateral decreases (supply channel) and an additional 1.6−2.8 basis points increase in the premium because the additional liquidity increases the demand for collateral (demand channel).

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1. Introduction

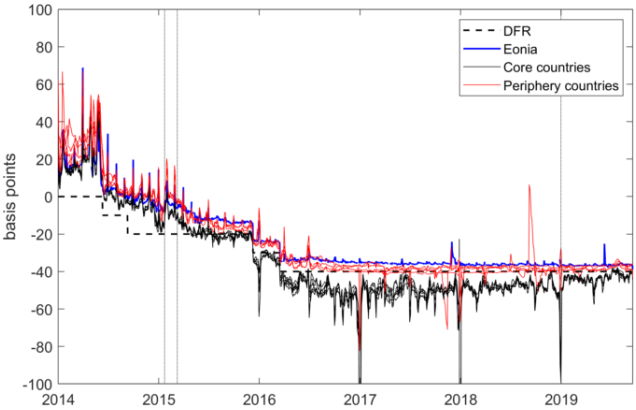
The introduction of unconventional monetary policy, especially Quantitative Easing (QE), has led to distortions in euro area money markets. Figure 1 documents two puzzling developments: First, after the onset of the European Central Bank's (ECB) Public Sector Purchase Programme (PSPP) in March 2015, short-term money market rates started to drift apart. Secured money market rates—especially those backed by high-quality collateral—diverged from unsecured rates and secured rates backed by less safe collateral. More precisely, the rates of general collateral (GC) repurchase agreements (repos) backed by collateral from the core euro area (black) moved away from the unsecured Euro Overnight Index Average (Eonia) (blue) and from repo rates backed by collateral from the euro area periphery (red).[1] These interest rate movements are puzzling because there is no material increase in credit risk that could explain a divergence in interest rates. In fact, the unsecured rate—which is sensitive to changes in credit risk—hardly moves. The second surprising development is the drop of core euro area repo rates below the ECB's deposit facility rate (DFR), represented by the dashed black line. The DFR constitutes the lower bound of the ECB's interest rate corridor and hence should also serve as a lower bound for money market rates. What explains these interest rate dynamics? How is it possible that the lower bound of the ECB's interest rate corridor does not hold?

We address these questions by providing a simple supply and demand framework for the money market employing the concept of cash- and collateral-driven market segments. Based on this framework, we illustrate that QE creates scarcity of high-quality collateral through a reduction in supply and increase in demand for safe assets. Both shocks simultaneously create downward pressure on repo rates leading to a *repo scarcity premium*. This premium is similar to classical convenience premia in government bond markets (e.g., Krishnamurthy and Vissing-Jorgensen, 2012; Nagel, 2016) as well as repo specialness premia (e.g., Duffie, 1996; Arrata et al., 2020; Corradin and Maddaloni, 2020). The premium enables us to explain the interest rate dynamics in euro area money markets presented in Figure 1. Our empirical results confirm that repos backed by high-quality collateral exhibit a scarcity premium, which is driven by the PSPP.

[1]The euro repo market is the largest market for euro interbank funding with a quarterly turnover of more than EUR 5.5 trillion (European Central Bank, 2015). It constitutes the secured money market in the euro area. A repo is a contract that stipulates the purchase and repurchase of a security. The repo buyer purchases the asset (mostly fixed-income securities) from the seller and commits to sell it back at a predetermined price in the future. The difference between the purchase and repurchase price determines the repo rate. The buyer effectively lends cash to the seller, which makes repos economically identical to collateralized loans. The collateral underlying a GC repo contract can be any security from a basket of many—often thousands—of securities.

Figure 1: Secured and unsecured money market rates

Figure 1 plots the unsecured interbank money market rate, Eonia (blue), as well as two secured interbank money market rates: The black lines show GC repo rates backed by collateral from core euro area countries (Austria, Belgium, Finland, France, Germany, and the Netherlands). The red lines plot GC repo rates backed by collateral from peripheral euro area countries (Ireland, Italy, Portugal, and Spain). The dashed line represents the ECB's deposit facility rate. Finally, the first vertical line indicates the announcement of the PSPP on 22 January 2015, the second line the start of the PSPP purchases on 9 March 2015, and the third line the preliminary end of the PSPP on 31 December 2018.



The scarcity premium has distributional consequences for the banking and non-bank sector and it raises concerns about the effectiveness of the ECB's monetary policy implementation.

In our supply and demand framework, we illustrate that QE creates scarcity of safe collateral by decreasing the supply and increasing the demand. The supply of collateral decreases because the central bank acts as a buy-and-hold investor of euro area government bonds. The demand increases because the additional liquidity from QE creates the need for safe stores of value. Only banks can deposit their liquidity safely at the central bank. Non-banks must use the secured money market—that is, the repo market—if they want to achieve a similar level of safety. This market segmentation creates additional demand for safe collateral in the repo market from non-banks. The growing scarcity of safe collateral triggers a transformation from cash- to collateral-driven markets indicating a fundamental shift in the usage of GC repo markets. Usually, GC repo markets are cash-driven, that is, market participants want to borrow or lend cash for the purpose of managing their liquidity (Boissay and Cooper, 2020). In a situation of collateral scarcity, however, market participants want to borrow or lend securities instead of

cash. GC repo markets thereby become similar to special collateral (SC) repo markets.[2]

Against this background, the GC repo scarcity premium has strong similarities to SC repo specialness (Duffie, 1996). It measures the scarcity of a security, or more precisely: a group of securities. However, repo specialness and repo scarcity premia differ in one important dimension: the reason why market participants are willing to pay these premia. Specialness represents the rental price of a specific security. Market participants are willing to pay the specialness premium because they need a specific security, for instance, to cover a short sale. The GC repo scarcity premium, on the other hand, is not driven by the demand for a specific security. Instead, it is driven by the demand for any securitiy that can serve as a safe store of value. For instance, all German government bonds have the same default risk and hence they serve equally well as a store of value in short-term repo contracts. Therefore, market participants are willing to pay the same scarcity premium for any German government bond, irrespective of the exact ISIN of this bond. Hence, repo specialness describes the scarcity of individual collateral and the repo scarcity premium describes the scarcity of a group of collateral with identical characteristics—in particular, identical credit risk.

Extant literature focuses on the interaction between the PSPP and SC repo markets. For instance, Arrata et al. (2020) and Corradin and Maddaloni (2020) present evidence for a positive effect of the PSPP on repo specialness leading to declining SC repo rates. The impact of the PSPP on SC repo rates runs exclusively through a supply channel. We add to this literature by extending the analysis to the GC repo market pointing to the important role of a joint supply and demand channel. Only by considering both channels we are able to explain the puzzling interest rate movements presented in Figure 1: First, the scarcity premium is not only driven by a reduction in the supply of collateral, but also by an increasing the demand for safe stores of value. Therefore, in particular repos backed by safe collateral exhibit a premium pushing these repo rates away from other money market rates. Second, the emergence of a scarcity premium goes hand in hand with safe repos becoming collateral-driven. Since the DFR only acts as a lower bound for cash-driven rates, safe repo rates can drop below the DFR as soon as they become collateral-driven.

In our empirical analysis, we document that only repos backed by collateral from core euro area countries exhibit an increasing scarcity premium during the first round of the PSPP between March 2015 and December 2018. We find that the premium for the collateral from a given jurisdiction begins to increase on average only after the ECB holds more than 9% of

[2]Contrary to GC repos, in a SC repo, the underlying collateral is known in advance. Hence, the collateral borrower knows exactly which specific security she will receive. Therefore, SC repo trades are usually driven by the supply and demand for specific securities.

the outstanding amount of government bonds. The premium reverts back to its pre-PSPP level after the end of the purchases. Additionally, we provide empirical evidence for the PSPP being a driver of the scarcity premium through a supply and demand channel. Purchasing 1% of outstanding government bonds increases the scarcity premium by 1.0−1.7 basis points through the supply channel. Simultaneously, the related increase in excess liquidity of about EUR 70 billion, leads to an increase in the scarcity premium by 1.6−2.8 basis points for high-quality collateral. The effect disappears for repos backed by collateral with lower credit ratings. These results square well with extant literature on SC repo markets. For instance, Arrata et al. (2020) find that a decrease in the supply of 1% of an outstanding bond during the PSPP decreases the repo rate of this bond by 0.8−5 basis points.

Our results have two major policy implications. First, the GC scarcity premium pushes GC repo rates below the DFR creating additional cost for safely storing liquidity for non-banks compared to banks. In a back-of-the-envelope calculation, Bechtel et al. (2021) find that between March 2015 and December 2018, the banking sector was able to save EUR 3.3−4.7 billion by having access to the ECB's deposit facility. Second, the GC scarcity premium hampers monetary policy implementation. The failure of the lower bound of the ECB's interest rate corridor raises concerns about the ability of the ECB to control short-term interest rates. The secured money market is about ten times bigger than the unsecured market (European Central Bank, 2015). Hence, secured (repo) rates are crucial for the transmission of monetary policy. Moreover, the lower bound is particularly important in an excess liquidity regime because in such a *floor system* (Keister, Martin, and McAndrews, 2008; Cúrdia and Woodford, 2011) short-term rates drop to the lower bound of the interest rate corridor making the DFR the effective policy rate. Our results suggest that there is a trade-off between the controllability of short-term and long-term rates. While the PSPP is successful in lowering long-term rates (e.g., Andrade et al., 2016; Eser et al., 2019; Lemke and Werner, 2020), we show that this comes at the cost of losing control over short-term rates.

We discuss the policy implications in more detail in Section 6. The rest of the paper is structured as follows: Section 2 provides an overview of the extant literature and how we contribute to it. Section 3 presents the difference between cash- and collateral-driven repo markets. Section 4 introduces the GC repo scarcity premium and derives testable hypotheses. In Section 5, we conduct our empirical analysis showing that the PSPP has a positive effect on the repo scarcity premium for repos backed by safe collateral. In Section 6, we discuss the policy implications of our findings and in Section 7, we conclude.

2. Literature

Our paper contributes to the literature that examines the interactions between QE and money market rates. The main channel that is discussed in this literature is the scarcity channel of SC repos. Corradin and Maddaloni (2020) examine how government bond purchases during the ECB's Securities Markets Programme affect SC repo rates in the Italian market. They show that government bond purchases decrease the supply of outstanding bonds and therefore increase the specialness of the targeted securities. Arrata et al. (2020) find similar results for SC repo rates during the PSPP. D'Amico, Fan, and Kitsul (2018) focus on the U.S. SC repo market and quantify the effect of QE on the scarcity value of Treasury collateral. We contribute to this literature by examining the effect of government bond purchases on GC repo rates. Contrary to the SC repo market and repo specialness, GC repos are not only affected by QE through a supply channel, but also through a demand channel. This demand channel is crucial for understanding the puzzling interest rate movements, that is, the drop of GC rates below the DFR as well as their divergence from other money market rates.

We also contribute to the literature on unconventional monetary policy and monetary policy implementation, in particular on the role of the money market for monetary transmission. One strand of this literature examines the failure of interest rate floors set by central banks. Bech and Klee (2011), Armenter and Lester (2015), Williamson (2019), and Martin et al. (2019) analyze the U.S. experience, where the federal funds rate dropped below the interest rate on reserves after liquidity injections by the Fed in 2008. In the euro area, on the other hand, unsecured money market rates did not drop below the lower bound, only secured rates did. By introducing the role of collateral, we add the necessary layer of complexity to explain the interest rate dynamics in the euro area. A second strand of this literature examines the role of the money market for the implementation and transmission of monetary policy. For instance, Ballensiefen, Ranaldo, and Winterberg (2020) argue that market segmentation in the market for central bank reserves hampers monetary policy transmission: Lending rates of banks with access to the deposit facility of the ECB are more disconnected from the policy rate than lending rates of banks without access. Ranaldo, Schaffner, and Vasios (2020) show that regulation puts downward pressure on repo rates. According to the European market infrastructure regulation (EMIR), European central counterparties must turn their unsecured cash holdings into highly liquid securities. To this end, they use the euro repo market. Arrata et al. (2020) argue that GC repo rates are the upper bound of SC repo rates and therefore GC rates below the DFR indicate that complete GC baskets can become special. We show that there is an important difference between SC and GC repo markets and between specialness and the GC scarcity premium, respectively. QE affects specialness only through a supply channel, but it affects

scarcity premia jointly through a supply and demand channel. This distinction has important implications for possible policy responses that aim at mitigating the premia. We briefly discuss these responses in Section 7.

Finally, we contribute to the ongoing discussion about whether a channel or a floor system is more appropriate for implementing monetary policy (e.g. Keister, Martin, and McAndrews, 2008; Cúrdia and Woodford, 2011). Goodfriend (2002) provides the theoretical foundation by showing that central banks are able to pay interest rates on reserves—which is a prerequisite for a floor system—and still make a profit as long as the yield curve has a positive slope. In a more recent study, Williamson (2019) constructs a two-sector general equilibrium model to study the functioning of a floor system. He points to the important fact that an increase in central banks' balance sheets, necessary to establish a floor system, can have redistributive effects and even reduce welfare. Our paper contributes to this literature by showing that it is important for the functioning of a floor system how the central bank increases its balance sheet to provide the interbank market with the necessary excess liquidity. If large-scale government bond purchases are used to establish the floor system, secured interbank markets may become collateral-driven leading to a scarcity premium. In such a scenario, the lower bound may not hold.

3. Cash- and collateral-driven money markets

In this section, we introduce the concept of cash- and collateral-driven money markets. We present a simple framework of supply and demand that enables us to understand how these markets differ. The framework will also help us understand why GC repo rates can drop below the DFR.[3]

3.1 Cash-driven money market

The upper panel of Figure 2 presents a schematic description of the cash-driven money market including the main market participants. The grey box illustrates the interbank segment, which is the core of the euro money market. Banks participate in this market because they want to borrow or lend cash, for example, to manage their liquidity balance. Ultimately, the supply and demand for cash originates from the customers of banks such as hedge funds, money market funds, and asset managers. Borrowing and lending in the cash-driven money market can be secured or unsecured. If it is secured, there is not only an exchange of cash as depicted by the solid lines, but also an exchange of collateral as shown by the dashed lines. If banks fail

[3]Existing studies that touch upon cash- vs. collateral-driven money markets include Brand, Ferrante, and Hubert (2019) and Schaffner, Ranaldo, and Tsatsaronis (2019).

to borrow or lend cash in the interbank market, they can use the standing facilities of the Eurosystem as a fallback option. More precisely, they can use the deposit facility to deposit cash overnight at the ECB and the marginal lending facility to borrow cash overnight from the ECB. The standing facilities are only open to banks.[4]

The classical example for a cash-driven market segment is the unsecured money market, which is by definition cash-driven since it does not involve collateral. However, the GC repo market is usually also classified as a cash-driven market because—contrary to SC repos—GC repos cannot be used to acquire specific collateral. GC repo baskets usually include thousands of different securities and the cash borrower is allowed to deliver any of these securities into the repo. Therefore, the cash lender does not know ex-ante which exact collateral she will receive.

Panel (a) of Figure 3 presents the supply and demand curves in the cash-driven money market. The demand curve is downward sloping: As the price of cash (the interest rate r) decreases, demand increases. The supply curve is upward sloping and has a lower bound at the DFR, r_{DF}: As the price of cash decreases, the supply decreases. When the interest rate falls below r_{DF}, the supply of cash drops to zero. The reason for this lower bound is the ability of banks to deposit unlimited amounts of liquidity at the deposit facility of the ECB. Consequently, banks have no incentive to lend cash at a rate below r_{DF}. The figure also illustrates that in a cash-driven money market, an increase in the supply of cash—that is, a rightward shift of the supply curve, for example, through QE—drives the cash-driven interest rate to its lower bound. This situation is known as a liquidity trap.

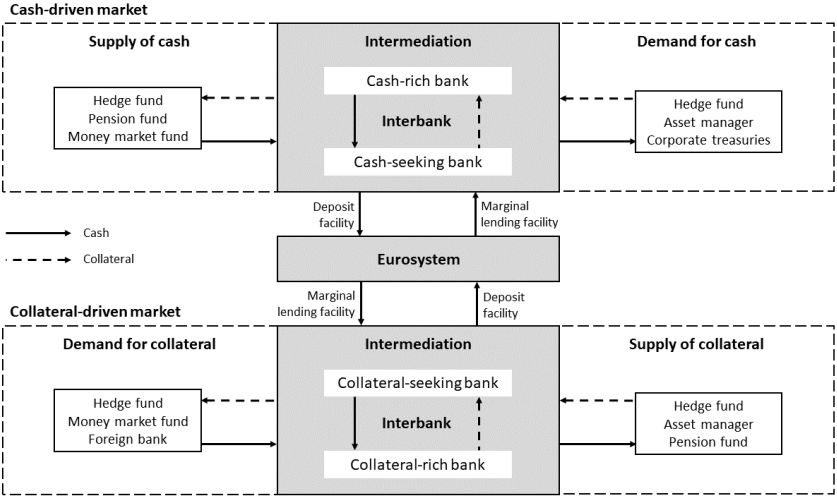
3.2 Collateral-driven money market

The lower panel of Figure 2 presents the collateral-driven segment of the euro money market. In this segment, banks participate because they want to borrow or lend securities. Ultimately, the supply and demand for securities originates from the customers of banks such as hedge funds, money market funds, and asset managers. The collateral-driven money market is by definition a secured money market because collateral has to be involved. Contrary to the cash-driven market segment, the deposit facility of the ECB does not serve as an alternative to collateral borrowers because it does not offer the possibility to source collateral. The classical example of a collateral-driven money market is the SC repo market. SC repos are usually used to acquire specific securities, for example, in order to cover short sales. Contrary to a GC repo, the cash lender knows exactly which security she will receive when using a SC repo.

[4]Banks and non-banks could also directly purchase government bonds to safely store their liquidity. However, contrary to repos, the outright purchase of a bond exposes the investor to price risk. In a repo, the repurchase price is fixed and therefore repos are more suitable for short-term liquidity management.

Figure 2: Cash- and collateral-driven money market

Figure 2 presents a schematic description of the euro repo market and its main market participants. The upper panel shows the cash-driven market segments and the lower panel the collateral-driven segments. The solid lines depict flows of cash and the dashed lines flows of collateral.



Panel (b) of Figure 3 presents the supply and demand curves in the collateral-driven money market. In this market segment, a bank supplies cash because it wants to borrow a security and not because it needs to manage its liquidity. Therefore, what used to be the demand for cash in the cash-driven market now becomes the supply of collateral, and the supply of cash becomes the demand for collateral. There is no lower bound for money market rates in the collateral-driven segment.

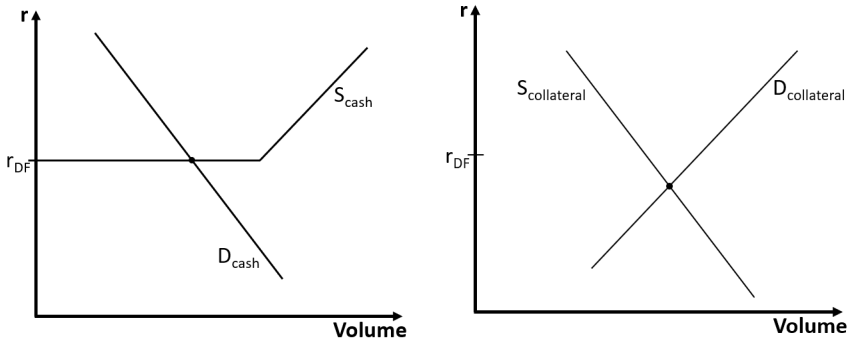
3.3 Empirical demand and supply

Figure 4 shows the empirical equivalent of Figure 3. Each dot represents one equilibrium rate-volume observation from three different segments of the money market: secured with collateral from the core euro area (Panel (a)), secured with collateral from the euro area periphery (Panel (b)), and unsecured (Panel (c)). The scatter plots suggest that the core euro repo market becomes collateral-driven while the other two segments remain cash-driven.

In the collateral-driven core repo market, equilibrium observations seem to be scattered around a relatively straight vertical line. Based on the framework presented in Panel (b) of Figure 3, this pattern is in line with a decrease in supply of collateral due to the large scale

Figure 3: Supply and demand in the cash- and collateral-driven money market

Figure 3 illustrates the supply and demand curves of the cash- and collateral-driven money market.



(a) Cash-driven money market **(b) Collateral-driven money market**

government bond purchases and an increase in demand due to the new liquidity in the system. In particular, it suggests that the decrease in supply roughly matches the increase in demand. Consequently, the trading volume remains approximately constant while the rate strongly decreases.

In the unsecured and peripheral secured market, equilibrium observations show that the lower bound holds. Consequently, these market segments are cash-driven. Following the framework presented in Panel (a) of Figure 3, this pattern is in line with an increase in the supply of cash and a decrease in the demand for cash. The supply increases because the PSPP increases the liquidity in the market. Due to this additional liquidity, the demand for cash in the private money market decreases. The negative shift in the demand curve can be observed in Panel (b) and (c) of Figure 4 along the (almost) fully elastic supply curve.

4. QE and the GC repo scarcity premium

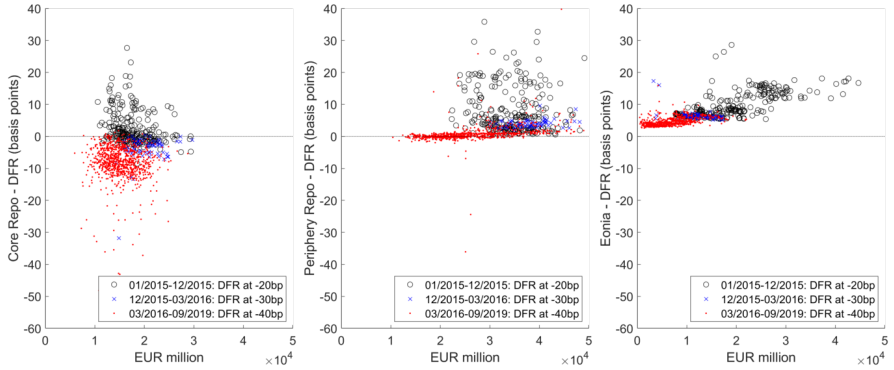
4.1 GC repo scarcity premium

In this section, we motivate how a cash-driven market can evolve into a collateral-driven market. To this end, we introduce the GC repo scarcity premium. It is defined as the difference between the GC repo rate and its cash-driven equivalent rate:

$$SP = r_{i,t}^{cash} - r_{i,t}, \tag{1}$$

Figure 4: Secured and unsecured money market spreads

Panel (a) to (c) of Figure 4 presents equilibrium rate-volume observations from the different segments of the money market. Rates are measured as spread to the DFR. The color-coding indicates different levels of the DFR and thereby chronologically orders the observations. Black dots represent equilibria between Janaury 2015 and December 2015, blue dots between December 2015 and March 2016, and red dots between March 2016 and September 2019. Panel (a) presents GC repo rate-volume observations with collateral from core euro area countries (Austria, Belgium, Finland, France, German, and the Netherlands). Panel (b) presents GC repo with collateral from peripheral euro area countries (Ireland, Italy, Portugal, and Spain). Finally, Panel (c) presents Eonia rate-volume observations.



(a) Secured (core) **(b) Secured (periphery)** **(c) Unsecured (Eonia)**

where $r_{i,t}$ is the repo rate backed by collateral from country i and $r_{i,t}^{cash}$ is the cash-driven equivalent. The cash-driven equivalent is the rate a certain GC repo contract would have if it was cash-driven, that is, if collateral from country i was not scarce. In this case, $r_{i,t}^{cash} = r_{i,t}$ and the scarcity premium is zero. In a collateral-driven repo market, $r_{i,t}^{cash}$ is unobservable because a GC repo basket can be either cash- or collateral-driven, but not both at the same time.

The GC repo scarcity premium is similar, but not identical to repo specialness. The two premia differ in the motivation why market participants are willing to pay them. Market participants are willing to pay the specialness premium because they need a specific security, for example, to cover a short sale. The GC scarcity premium, on the other hand, is not related to a specific security, but to a basket of securities. Therefore, it cannot be driven by the demand for an individual government bond. Instead—as we will argue in more detail below—the GC scarcity premium is driven by the demand for safe stores of value. Since all German government bonds have the same credit risk, they serve equally well as a store of value in short-term repo contracts. Therefore, market participants are willing to pay the scarcity premium for any German government bond, irrespective of the exact ISIN of this bond. In a nutshell, repo specialness measures the scarcity of individual securities and the scarcity premium measures

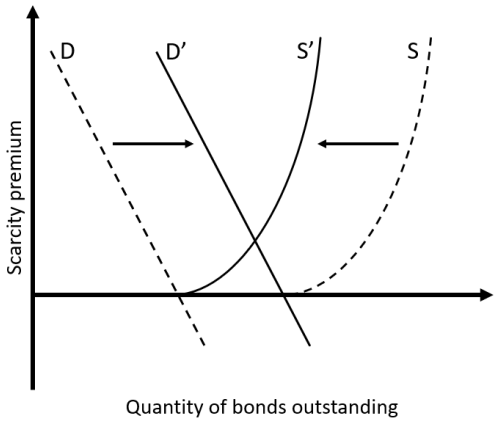
the scarcity of a group of securities with identical credit risk.

Figure 5 illustrates how the scarcity premium is related to the supply and demand for collateral in the repo market. The figure is similar to illustrations from the repo specialness literature (e.g., Duffie, 1996; Krishnamurthy, 2002; Arrata et al., 2020). However, we apply this concept to the GC repo market. Hence, D is the demand curve for GC collateral in the repo market. S is the supply curve for GC collateral available for lending in the repo market. The supply curve becomes flat at a scarcity premium of zero, that is, at the cash-driven GC repo rate. Banks have no incentive to supply collateral—that is, to borrow cash—for a rate that is higher than the cash-driven rate. Hence, theoretically the scarcity premium cannot become negative.

The dashed lines in Figure 5 illustrate the supply and demand for collateral in a cash-driven repo market. The supply of collateral exceeds demand and hence the scarcity premium is zero. Put differently, there is an abundance of collateral and the market is driven by the supply and demand for cash. This is how the GC repo market used to function. However, evidence presented in Figure 1 and Figure 4 suggests that at least certain segments of this market have become collateral-driven after the start of the PSPP.

Figure 5: GC scarcity premium (theory)

Figure 5 illustrates how GC repo baskets can trade at a scarcity premium when the supply of bonds in the repo market decreases and the demand increases. Theoretically, the scarcity premium is the difference between the GC repo rate and its cash-driven equivalent. The supply curve becomes flat at zero because banks have no incentive to supply collateral for a higher rate than the cash-driven rate.



The solid lines in Figure 5 show how a cash-driven market can transform to a collateral-driven

market during QE. Large-scale government bond purchases have two effects on the GC repo market: First, they decrease the supply of available collateral because the central bank reduces the amount of available government bonds in the market acting as a buy-and-hold investor. Second, government bond purchases leave financial and non-financial institutions with additional liquidity. Since only euro area banks can deposit this liquidity safely in the deposit facility of the ECB, non-banks and foreign banks have to look for alternatives. GC repos—especially those backed by high-quality collateral—are a natural choice for safely storing liquidity. Therefore, the demand for (high-quality) collateral increases during QE. The intersection of S' and D' in Figure 5 present the new equilibrium. The negative shock to the supply and simultaneous positive shock to the demand for collateral render collateral scarce. Consequently, the scarcity premium becomes positive and the market is now collateral-driven.

4.2 Testable hypotheses

Based on the discussion in the previous sections, we can derive the following testable hypotheses about the effect of QE on the GC repo market:

(H1) *The scarcity premium increases when the supply of collateral decreases.*

This follows directly from the discussion of Figure 5. Ceteris paribus, a decreasing supply of available collateral in the repo market increases the repo scarcity premium.

(H2) *The scarcity premium increases when the demand for collateral increases.*

This follows directly from the discussion of Figure 5. Ceteris paribus, an increasing demand for collateral in the repo market increases the repo scarcity premium.

(H3) *The scarcity premium mainly increases for repos backed by high-quality collateral because the demand for this collateral increases.*

The demand for GC is driven by the need to safely store liquidity from QE. Therefore, demand should increase mainly for high-quality collateral leading to higher scarcity premia for repos backed by this collateral.

5. Empirical analysis

5.1 Data

We use a trade-by-trade dataset of euro GC interbank repo transactions from the three major repo exchanges in the euro area: BrokerTec, Eurex Repo, and MTS. The dataset includes transactions from January 2014 to September 2019. For each transaction, the following information

is available: time of the trade, collateral basket, tenor, trade volume, and repo rate. Each basket contains government bonds from a euro area country. Our dataset contains baskets for the following ten countries: Austria, Belgium, Finland, France, Germany, Ireland, Italy, the Netherlands, Spain, and Portugal. We aggregate the data at the basket level and compute volume-weighted average monthly repo rates. We focus exclusively on overnight repos in order to ensure that differences in repo rates across baskets are not driven by differences in average maturities.[5] As common in the literature, in order to control for end-of-quarter effects (e.g., Munyan, 2015), we exclude the last day of each quarter from the regression analysis. It is worth mentioning that leaving these observations in does not qualitatively change any of the results in this paper.

The euro repo market is the largest market for euro interbank funding with a quarterly turnover of more than EUR 5.5 trillion (European Central Bank, 2015). BrokerTex, Eurex, and MTS are not only repo exchanges, but they also take the role of a central counterparty (CCP). They step in between the lender and the borrower and become the borrower to every lender and the lender to every borrower. Thereby, trading becomes anonymous and the CCP takes over counterparty credit risk.[6] Boissel et al. (2017) show that credit risk is still priced in CCP-based repo markets through CCP and CCP-member default risk.

We merge our repo dataset with monthly purchases from the PSPP and excess liquidity holdings data. The ECB publishes monthly excess liquidity holdings as well as purchase volumes for each euro area country separately on its website.[7] For each country i in our repo dataset, we construct the variable $PSPP_{i,t}$. It measures the share of government bonds of country i that is available in the open market in month t. This share is reduced by the ECB during the PSPP because the central bank acts as a buy and hold investor. For instance, if in month t the ECB holds 10% of the outstanding bonds of country i on its balance sheet, $PSPP_{i,t}$ takes the value 90%. Since $PSPP_{i,t}$ is not stationary, we use it in first differences in the regression. The change in the aggregate amount of excess liquidity holdings ΔEL_t measures the total amount of additional liquidity entering the market in month t. It serves as a proxy for the demand pressure for collateral in the repo market.

The PSPP was formally announced in January 2015 and further implementation details were communicated in March 2015, which also marks the start of the large scale asset purchases. The

[5]Overnight repos account for almost 90% of the trading volume in the euro GC repo market.

[6]For more information on the euro repo market, see Mancini, Ranaldo, and Wrampelmeyer (2016) and Ranaldo, Schaffner, and Vasios (2020).

[7]Excess liquidity is defined as the current account holdings of banks plus their deposit facility holdings less their minimum reserve requirements.

policy rationale of the PSPP was to provide additional monetary policy accommodation in a situation in which policy rates could not be cut (much) further. The initial monthly envelope of the PSPP purchases was EUR 60 billion, which was increased in April 2016 to EUR 80 billion and then decreased again to EUR 60 billion in April 2017. In December 2017, the purchase volume has been reduced to EUR 30 billion and in October 2018 to EUR 15 billion. The net purchase phase of the PSPP lasted until December 2018.

From January to September 2019, the ECB only replaced maturing securities, that is, the PSPP had entered the reinvestment phase, which was announced to continue until the monetary policy accommodation provided by PSPP reinvestments is no longer needed. Between March 2015 and December 2018, the Eurosystem purchased euro area government bonds, agency bonds, and euro area supras worth close to EUR 2.2 trillion. The purchase volumes were split according to the capital key of the member countries at the ECB. In other words, each national central bank of the Eurosystem purchased the share of the monthly PSPP envelope that corresponds to its capital share, exclusively focusing on the government bonds of their own country.

Our dataset brings about one limitation: Ideally, we would use OTC repo data in order to directly measure the repo rates paid by non-banks. However, OTC repo transactions are recorded only since July 2016 in the ECB's proprietary MMSR dataset. This dataset does not distinguish between GC and SC repos, which makes it impossible to compute a reliable measure of the GC repo scarcity premium. Eisenschmidt, Ma, and Zhang (2020) show that non-banks can access the repo market only at significantly higher costs than banks. According to their analysis, non-banks pay between $10-15$ basis points higher rates than banks. However, since they rely on MMSR data, the drawback of their approach is that a clean separation between GC and SC repos is not possible and hence the estimated spread is likely biased upwards. In any case, the results presented in this paper are a lower bound of the actual scarcity premium paid by non-banks.

5.2 Methodology

In order to test our hypotheses, we first need to measure the scarcity premium SP for the individual GC repo baskets. Recall that SP is defined as the spread between the repo rate r and its cash-driven equivalent r^{cash}. We need a proxy for the cash-driven equivalent rate because it is unobservable. In our main regression analysis, we use Eonia as the cash-driven rate because we can be 100% certain that this rate is only driven by the supply and demand for cash.

In order to quantify the effect on SP of changes in the supply and demand for collateral,

we aggregate all variables to a monthly frequency and run the following regression:

$$\begin{aligned} SP_{i,t} = \alpha SP_{i,t-1} + \beta \Delta PSPP_{i,t} + \delta \Delta EL_t + \kappa(\Delta EL_t \times Rating_{i,t}) \\ + \gamma_1 \Delta VSTOXX_t + \gamma_2 \Delta CDS_{i,t} + \gamma_3 SLF_t + \eta_i + \varepsilon_{i,t}, \end{aligned} \tag{2}$$

where $\Delta PSPP_{i,t}$ is the change in the share of government bonds available in the open market. ΔEL_t measures the change in total excess liquidity holdings. $Rating_{i,t}$ is the Standard&Poors sovereign credit rating mapped to a numerical scale as shown in Table 3. We cluster standard errors at the country- and month-level. Since we intend to identify time-varying effects common to all variables, we do not include time fixed effects and instead add several control variables: $VSTOXX_t$ is an aggregate measure for volatility. It reflects the investor sentiment and overall economic uncertainty by measuring the 30-day implied volatility of the EURO STOXX 50. $CDS_{i,t}$ captures the CDS rates of country i controlling for idiosyncratic innovations in credit risk. SLF_t is a dummy variable for the time after the introduction of cash collateral in the ECB's securities lending facility on 15 December 2016. Through this facility, the ECB lends part of its securities against cash channeling back some of the collateral to the market. However, the total volume is restricted to EUR 50 billion. Additionally, we add the first lag of the dependent variable to control for any persistence in the scarcity premium. Finally, η_i represents country fixed effects and $\varepsilon_{i,t}$ is the error term.[8] We estimate Equation (2) both as simple OLS and using the Arellano and Bond (1991) dynamic panel estimator in order to control for the Nickell bias that is introduced by adding the first lag of the dependent variable as a regressor.

In essence, Equation (2) estimates the GC scarcity premium as a function of both the supply and demand for collateral in the repo market. The change in the outstanding amount of available government bonds $\Delta PSPP_{i,t}$ proxies the supply of collateral from country i in the repo market. The total change in excess liquidity holdings ΔEL_t measures the additional liquidity that enters the market. This liquidity creates a demand for collateral in the repo market as safe store of value. In order to distinguish between price effect for repos with different collateral quality, we introduce the interaction term $Purchases \times Rating$.

The above regression design is similar to empirical approaches in the literature that examine the impact of QE on repo specialness (e.g., D'Amico, Fan, and Kitsul, 2018; Arrata et al., 2020). One endogeneity concern in this literature is reverse causality because the ECB has communicated that it may take into account repo specialness in its PSPP purchases. For instance, if a certain German government bond trades on special, the ECB might abstain from buying this bond. Fortunately, this concern does not apply to GC repo markets and the GC

[8] For more information about all variables used in the empirical analysis, see Table D.1 in the Appendix.

repo scarcity premium. The ECB has committed to specific monthly purchase volumes following the capital key of its member countries. Consequently, while the ECB can react flexibly to specialness of individual bonds, it has no leeway when it comes to adjusting total purchase volumes. Against this background, $\Delta PSPP_{i,t}$ and ΔEL_t can be treated as exogenous.

5.3 Results

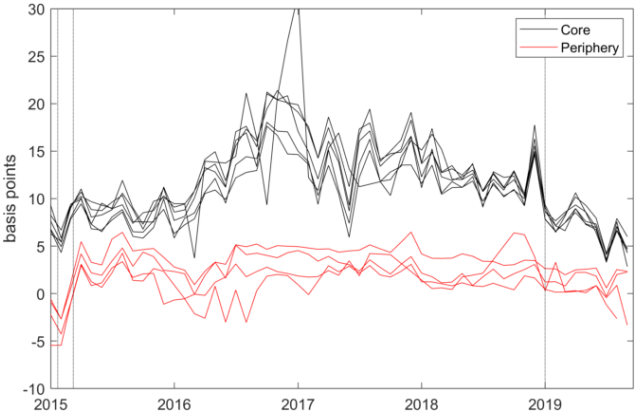
Scarcity premium

Figure 6 plots the scarcity premia for collateral from our sample of euro area countries. The first vertical line indicates the announcement of the PSPP on 22 January 2015, the second line marks the start of the purchases on 9 March 2015, and the third line the end of the program on 31 December 2018. The scarcity premia of core euro area countries start increasing in early 2016 and reach a peak at the end of 2016. Afterwards, they remain at an elevated level of about $10-20$ basis points until the end of the PSPP in December 2018, before coming back to pre-PSPP levels. The observation that scarcity premia do not increase immediately after the start of the PSPP purchases is in line with our concept of cash- and collateral-driven markets: Before the PSPP, GC repo markets are cash-driven meaning collateral supply exceeds demand. Therefore, it requires continuous government bond purchases by the central bank until bonds from certain issuers become scarce. The scarcity premium starts increasing after the central bank holds on average 9% of the outstanding bonds of the euro area core countries. Additionally, the size and variability over time of the scarcity premium is in line with the idea that monthly purchases create demand pressure. The premium is especially big during the time when monthly purchase volumes are at their peak. The scarcity premia of peripheral euro area countries remain close to zero over the whole period.

Table 1 presents summary statistics for the scarcity premium and all other variables used in the empirical analysis. The average scarcity premium for core countries between March 2015 and September 2019 is 11.58 basis points with a standard deviation of 4.13 basis points. The average scarcity premium of peripheral countries is 2.28 basis points and exhibits considerably less variation with a standard deviation of only 1.84 basis points. The fact that the scarcity premium of peripheral countries hardly varies indicates that the peripheral repo rates move in parallel with the cash-driven rate and therefore the peripheral repo market can be classified as cash-driven. Table 1 also shows that the ECB increases its share of government bond holdings ($\Delta PSPP$) by about 0.5% per month. The average increase in excess liquidity (ΔEL) amounts

Figure 6: GC scarcity premium (empirics)

Figure 6 plots the scarcity premium of the six core euro area countries in black (Austria, Belgium, Finland, France, Germany, and the Netherlands) and the four peripheral euro area countries in red (Ireland, Italy, Portugal, and Spain). We measure the scarcity premium as the spread between the GC rate of the respective country and Eonia. The first vertical line indicates the announcement of the PSPP on 22 January 2015, the second line the start of the PSPP purchases on 9 March 2015, and the third line the preliminary end of the PSPP on 31 December 2018.



to almost EUR 30 billion.[9]

Table 1: Summary statistics

Table 1 presents summary statistics for all variables between March 2015 and September 2019.

	Mean	Median	Std	Min	Max	N
SP (bp)	7.93	7.72	5.69	−3.32	31.51	540
SP_{Core} (bp)	11.58	11.06	4.13	−2.84	31.51	328
$\text{SP}_{Periphery}$ (bp)	2.28	2.25	1.84	−3.32	6.48	212
$PSPP$ (%)	83.49	82.55	9.26	62.22	99.59	540
$\Delta PSPP$ (%)	−0.46	−0.48	0.42	−2.47	1.52	530
ΔEL (EURbn)	29.55	27.74	42.64	−83.02	209.77	530
Rating	4.31	2.00	3.54	1.00	12.00	540
$\Delta VSTOXX$	−0.06	−0.56	3.62	−8.49	9.31	530
ΔCDS	−0.39	−0.39	10.51	−53.30	112.16	530

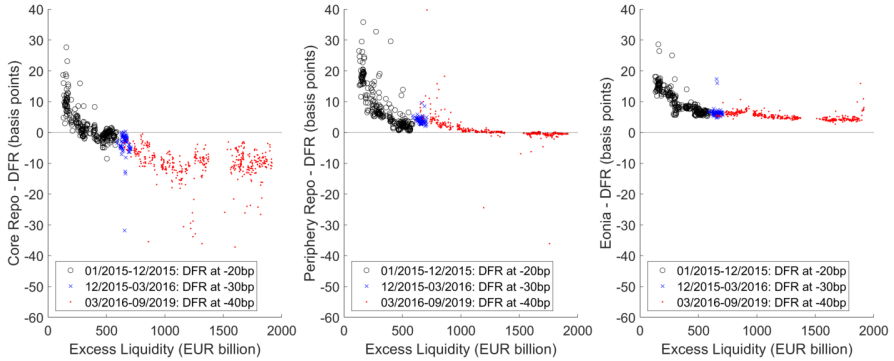
Figure 7 provides preliminary evidence for the relation between the PSPP and an increasing scarcity premium for secured core money market rates. It plots the spread of core GC repo

[9]Note that these averages include post-PSPP observations from January 2019 to September 2019, where no purchases have taken place. During the PSPP, that is, between March 2015 and December 2018, the average increase in the ECB's share of government bond holdings ($\Delta PSPP$) amounts to 0.55% and the average increase in excess liquidity (ΔEL) to EUR 38 billion.

rates (Panel (a)), peripheral GC repo rates (Panel (b)), and unsecured rates (Panel (c)) to the DFR against the excess liquidity in the Eurosystem. The three panels capture the fact that when the liquidity supply increases, money market rates decrease and vice versa. In line with previous observations, the figure suggests that core repo markets become collateral-driven as soon as there is enough excess liquidity in the system, while unsecured and peripheral segments remain cash-driven. This pattern is in line with the idea that high-quality collateral is used as a safe store of value to store the additional liquidity the enters the market through the PSPP.

Figure 7: Secured and unsecured money market spreads

Panel (a) to (c) of Figure 7 plot the spread of different money market rates relative to the deposit facility rate (DFR) against the excess liquidity in the Eurosystem. Panel (a) captures daily observations of repos backed by government bonds from the core euro area, that is, from Austria, Belgium, Germany, Finland, France, Luxembourg, and the Netherlands. Panel (b) covers repos backed by government bonds from the euro area periphery, that is, from Greece, Ireland, Italy, Portugal, and Spain. Lastly, Panel (c) presents rates from Eonia, that is, from the unsecured money market. Every dot represents one trading day. The three colors identify three periods with different levels of the DFR between January 2015 and September 2019.



(a) Secured (core) **(b) Secured (periphery)** **(c) Unsecured (Eonia)**

Regression analysis

Table 2 presents the results of our main regression analysis. Columns (1)−(3) summarize the results of the OLS regression with bank fixed effects and different combinations of control variables. In column (4), we run the two-step Arellano and Bond (1991) dynamic panel estimator. The coefficients of our proxies for supply and demand for collateral have the expected signs and are statistically as well as economically significant. The R^2's are high indicating that our explanatory variables explain most of the variation in the scarcity premium. The economic interpretation of our results is as follows: A 1% decrease in the outstanding amount of government bonds from country i (equivalent to less than two months of average purchases), increases

the scarcity premium by 1.0−1.7 basis points through the supply channel. Simultaneously, an equivalent average increase of excess liquidity, which amounts to about EUR 70bn, leads to an increase in the scarcity premium through the demand channel of 1.7−2.8 basis points for the top-rated government bonds (Germany and the Netherlands) and 1.6−2.7 basis points for the other core euro area countries (Austria, Belgium, Finland, and France). The effect becomes insignificant for collateral with low credit ratings.[10] Consequently, our results suggest that an increase in excess liquidity creates demand pressure for high-quality collateral. The effect disappears for more risky collateral, that is, for government bonds from the euro area periphery.

These findings complement the literature on QE and specialness, which finds that QE affects SC repo markets and specialness exclusively through a supply channel, that is, through a reduction in the supply of collateral. For instance, Arrata et al. (2020) find that a decrease in the supply of 1% of an outstanding bond during the PSPP decreases the repo rate of this bond by 0.8−5 basis points. In the GC repo market, on the other hand, the effect runs simultaneously through a supply and demand channel. The demand for high-quality collateral is an important additional driver of the repo scarcity premium.

Recall that our repo data captures only interbank markets. Hence, we are unable to observe the repo rates paid by non-banks directly. Against this background, there exists one alternative explanation for our results: It could be that the demand for safe collateral is not driven by non-bank customers looking for safe stores of value, but by the banks themselves. Credit institutions need to fulfil the Basel III capital and liquidity requirements such as the Liquidity Coverage Ratio, which forces them to hold an adequate stock of high-quality liquid assets (HQLA). Therefore, banks might be willing to pay a premium to source HQLA and hence time-varying demand for HQLA could be driving our results.

However, there are several reasons that speak against this interpretation: First, as illustrated in Figure 2 and as shown empirically by Eisenschmidt, Ma, and Zhang (2020), banks mainly play the role of an intermediary in the interbank GC repo market. They act on behalf of their customers instead of trading for their own books. Second, the timing of the repo rate movements fits perfectly to the introduction of the PSPP and less to changes in regulatory requirements. Third, core and peripheral bonds are both HQLA and hence if the demand pressure comes directly from banks, peripheral repo rates should be equally affected by the PSPP. Consequently, the HQLA argument does not square with the observation that core and peripheral repo rates start to diverge after the start of the PSPP. Therefore, while we cannot totally exclude that time-varying demand for HQLA from banks plays some role, it seems

[10] Table 3 provides an overview of our mapping from Standard&Poor's sovereign credit ratings to numbers between 1 and 11.

Table 2: Regression results

Table 2 presents the main regression results. It quantifies the effect of changes in supply and demand for collateral on the scarcity premium. The data has a monthly frequency. Columns (1)−(3) are estimated using simple OLS. Column (4) presents the results of a dynamic panel regression using the Arellano and Bond (1991) estimator. In order to keep the number of instruments small and avoid instrument proliferation, we restrict lags for the GMM moment conditions to two. t-statistics are shown in parentheses. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	(1) $SP_{i,t}$	(2) $SP_{i,t}$	(3) $SP_{i,t}$	(4) $SP_{i,t}$
$\Delta PSPP_{i,t}$	-168.6**	-101.0**	-142.8**	-113.0***
	(-2.63)	(-2.31)	(-2.66)	(-2.91)
ΔEL_t	0.0368***	0.0254***	0.0266***	0.0403***
	(3.25)	(3.63)	(3.68)	(10.60)
$\Delta EL_t \times Rating_{i,t}$	-0.00327**	-0.00196**	-0.00188**	-0.000876
	(-2.86)	(-2.70)	(-2.52)	(-1.56)
$SP_{i,t-1}$		0.602***	0.577***	0.538***
		(9.98)	(8.89)	(6.93)
$\Delta VSTOXX_t$			0.0207	-0.0139
			(0.35)	(-0.53)
ΔCDS_t			0.00467	0.0200***
			(0.71)	(2.65)
SLF			0.761	3.408***
			(1.58)	(2.96)
Constant	6.551***	2.195***	1.699**	
	(16.59)	(4.39)	(3.19)	
Bank FE	Y	Y	Y	Y
N	530	530	530	514
R^2	0.740	0.846	0.849	
Adj. R^2	0.734	0.842	0.845	
Instruments				14
AR(1) p-value				0.0226
AR(2) p-value				0.0657
Hansen p-value				0.783

unlikely that it is the dominant force behind the repo rate movements in the euro area during the implementation of the PSPP.

Table 3: Sovereign credit ratings

Table 3 presents our mapping between Standard&Poors sovereign credit ratings and a numeric scale from 1 to 11.

Sovereign credit rating	*Rating*	Countries' average rating
AAA	1	Germany, the Netherlands
AA+	2	Austria, Belgium, Finland, France
AA	3	
AA-	4	
A+	5	Ireland
A	6	
A-	7	
BBB+	8	Spain
BBB	9	
BBB-	10	Italy
BB+	11	Portugal

5.4 Robustness checks

As a robustness check, we use two alternative measures for the repo scarcity premium. First, we use the spread between the individual GC repo rates and the rate of the GC Pooling ECB EXTended basket from Eurex Repo. The basket includes approximately 14,000 securities that are eligible for open market operations at the ECB and have been rated at least BBB−/Baa3. Consequently, the range of possible securities a cash lender might receive as collateral from this basket is huge and therefore the GC Pooling ECB EXTended rate is an ideal candidate for a secured cash-driven rate.[11] The second alternative for measuring the repo scarcity premium is the spread between the individual GC repo rates and the DFR.

Table 4 presents the results of our robustness check. Broadly speaking, the results remain intact. The demand channel shows slightly less economic significance in case of the first alternative measure $SP_{i,t}^{EXT}$. The supply channel, on the other hand, slightly loses statistical significance in case of the second alternative measure $SP_{i,t}^{DFR}$. Columns (3) and (4) are also

[11] The addendum "Pooling" reflects the internationality of the basket. Compared to common GC baskets, covering only one country, the GC Pooling ECB EXTended basket includes bonds from Austria, Belgium, Finland, France, Germany, Ireland, Italy, Luxembourg, Malta, Slovakia, Slovenia, Spain, the Netherlands, and international Eurobonds (XS ISINs). The bond issuer must be established in the European Economic Area (EEA) or in one of the non-EEA G10 countries (that is, the U.S., Canada, Japan, or Switzerland). Cash lenders using the GC Pooling ECB EXTended basket may receive any of the 14,000 securities from various jurisdiction as collateral. Therefore, it seems very unlikely that this basket is used to source a specific security. Instead, we assume that the repo rate of the ECB EXTended basket is driven by the supply and demand for cash.

a direct test of the determinants that push the repo rate below the DFR. It seems as if the demand channel dominates suggesting that it is mainly the demand for safe stores of value that leads to a failure of the lower bound of the ECB's interest rate corridor.

Table 4: Robustness check: Alternative measures for the repo scarcity premium

Table 4 presents the regression results of our robustness checks. It quantifies the effect of changes in supply and demand for collateral on the scarcity premium. Columns (1) and (2) proxy the scarcity premium as spread to the GC Pooling ECB EXTended rate and Columns (3) and (4) as spread to the DFR. The data has a monthly frequency. Columns (1) and (3) are estimated using simple OLS. Columns (2) and (4) use the Arellano and Bond (1991) dynamic panel estimator. t-statistics are shown in parentheses. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	(1) $SP_{i,t}^{EXT}$	(2) $SP_{i,t}^{EXT}$	(3) $SP_{i,t}^{DFR}$	(4) $SP_{i,t}^{DFR}$
$\Delta PSPP_{i,t}$	-147.9**	-164.0***	-117.1*	-228.6
	(-2.72)	(-3.60)	(-2.26)	(-0.95)
ΔEL_t	0.0164*	0.0125***	0.0225***	0.0330***
	(2.15)	(3.10)	(3.47)	(3.91)
$\Delta EL_t \times Rating_{i,t}$	-0.00186**	-0.00130**	-0.00174**	-0.00235***
	(-2.66)	(-2.33)	(-2.34)	(-4.76)
$SP_{i,t-1}$	0.587***	0.572***	0.665***	0.530***
	(6.93)	(7.57)	(10.72)	(3.71)
$\Delta VSTOXX_t$	0.0763	0.0559**	0.0453	-0.0154
	(1.42)	(2.14)	(0.75)	(-0.55)
ΔCDS_t	-0.00209	0.00454	0.00319	0.0214**
	(-0.35)	(1.01)	(0.61)	(1.96)
SLF	0.872	5.838***	1.171*	6.129*
	(1.64)	(2.67)	(1.99)	(1.77)
Constant	-0.0384		-0.612	
	(-0.08)		(-1.28)	
Bank FE	Y	Y	Y	Y
N	530	514	530	514
R^2	0.832		0.868	
Adj. R^2	0.827		0.864	
Instruments		14		14
AR(1) p-value		0.0171		0.0209
AR(2) p-value		0.0845		0.236
Hansen p-value		0.253		0.486

6. Policy implications

Our results have several important implications for market participants, policy makers, academics, and regulators. First, the drop of core repo rates below the DFR drives a wedge between the cost of safely storing liquidity for banks versus non-banks. While banks can access the deposit facility at the ECB, non-banks are forced to rely on private repo markets with high-quality collateral if they want to minimize their counterparty risk. Bechtel et al. (2021) use the term *safe storage premium* to describe this additional cost. Their back-of-the-envelope calculation suggests that the banking sector is able to save EUR 3.3−4.7 billion between March 2015 and December 2018 by having access to the ECB's deposit facility.

Second, GC repo market segments backed by high-quality general collateral have completely changed their role. The core function of these market segments used to be to facilitate the reallocation of liquidity within the banking sector. However, after the start of the PSPP, rather than being a vehicle to reallocate cash, the safest segments of this market now facilitate reallocating collateral. Therefore, interest rates in these markets no longer reflect the supply and demand for cash, but the supply and demand for collateral, pushing these rates below the DFR. This development raises concerns about the ability of the ECB to steer short-term interest rates. Not being able to control short-term rates means not being able to control the first step of the transmission mechanism of monetary policy. The effectiveness of the lower bound becomes even more important in light of the high levels of excess liquidity, which drive money market rates towards the lower bound, making the DFR the effective policy rate. Such a system is known as a *floor system* (e.g., Keister, Martin, and McAndrews, 2008; Cúrdia and Woodford, 2011). The common perception is that in a floor system, the central bank can perfectly steer short-term interest rates by changing the lower bound of the corridor. However, the existence of repo scarcity premia cast doubts on the functionality of such a system in the euro area.

Against this background, the question arises if the ECB should take into account repo scarcity premia when conducting large scale government bond purchases. Scarcity premia have important unintended consequences leading to additional safe storage cost for non-banks as well as a failure of the lower bound of the ECB's interest rate corridor. Our results suggest that it matters for the functionality of the lower bound and the floor system how the excess liquidity—which is necessary to establish such a system—enters the market. If the introduction of a floor system is realized or accompanied by QE, the central bank has to make sure that the market for purchased securities is deep enough such that government bonds do not become scarce and render the market collateral-driven. Otherwise, the floor system becomes ineffective and rates drop below the lower bound. Put differently, in an excess liquidity regime there seems to be a trade-off between the ECB's ability to control short-term interest rates and its ability

to affect long-term interest rates through government bond purchases.

7. Conclusion

Euro area short-term interest rates diverged and partially even fell below the deposit facility rate—the effective lower bound—after the start of the Public Sector Purchase Programme in March 2015. In this paper, we provided a conceptual framework that enables us to understand these puzzling interest rate dynamics. We showed that the structure and functioning of certain segments of the GC repo market has changed. In particular, GC repos backed by high-quality collateral convert from being cash-driven to being collateral-driven. Collateral-driven repo rates carry a scarcity premium that increases with an increasing scarcity of safe assets. In our empirical analysis, we showed that a reduction in the supply and increase in the demand for repos backed by safe assets is a major driver of the scarcity premium. While the supply channel is already known in the literature on SC repos, the demand channel is new and only exists in GC repo markets. Our results have important distributional consequences for non-banks because non-banks have to pay a premium for safely storing their liquidity. Moreover, repo rates below the deposit facility rate raise concerns about the ECB's ability to control short-term interest rates, which is particularly worrisome in a floor system.

What are possible ways to reduce the repo scarcity premium? Policy makers and regulators can either try to mitigate the supply or the demand shock from QE. To mitigate the effects of the negative supply shock and to increase the availability of collateral, the ECB could increase the volumes of its securities lending facility. A similar facility in the U.S., the reverse repurchase facility of the Fed, has helped to alleviate the pressure on repo rates (e.g., Anderson and Kandrac, 2018). To mitigate the effects of the positive demand shock, the ECB could give non-banks access to its balance sheet, that is, to the deposit facility. This would allow non-banks to access a safe store of value and make them less dependent on the repo market.

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Appendix D.

D.1. Variable description

Table D.1: Variable descriptions

Table D.1 describes the variables used in the regression analysis.

Variable	Description	Frequency	Source
SP	Scarcity premium	daily	Repo data
PSPP	Share of government bonds available in open market	monthly	ECB
EL	Excess liquidity	monthly	ECB
Rating	Standard&Poors sovereign credit ratings	daily	S&P
VSTOXX	EURO STOXX 50 implied volatility index	daily	Bloomberg
CDS	CDS spreads	daily	Bloomberg
SLF	Dummy capturing acceptance of cash collateral in securities lending facility	daily	ECB

Part III

Appendix

Supplemental Appendix for Liquidity Risk and Funding Cost

Funding liquidity risk channel: Motivation

According to the funding liquidity risk channel, higher funding liquidity risk should lead to a higher demand for immediacy as well as higher funding cost. Table I.1 presents the results of two pooled panel regressions using yearly repo and balance sheet panel data that provide empirical evidence for this link. We proxy the funding liquidity risk of banks via their reliance on short-term wholesale funding. More precisely, we compute the share of short-term (less than one year) over total wholesale funding. We measure funding costs as the relative frequency of having a positive excess rate RF. A relative frequency of 0.5 implies that banks pay more than the daily volume-weighted average repo rate in 50% of their trades. This measure is robust to outliers and by construction between 0 and 1. We introduced it in Section 4.4.

In line with the funding liquidity risk channel, Column (1) of Table I.1 shows that a 10% increase in the share of short-term wholesale funding leads to a 2.1% increase in the market order share of banks and a 2.3% increase in funding cost, meaning the probability of paying more than the volume-weighted market average increases by 2.3%.

Table I.1: Pooled panel regression

Table I.1 presents the results of two pooled panel regressions. We use the share of short-term (less than one year) over total wholesale funding as a proxy for funding liquidity risk. Funding cost is measured as the relative frequency of having a positive excess rate RF, introduced in Section 4.4. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	(1)	(2)
	Market order share	Funding Cost
Share ST wholesale funding	0.210***	0.228***
	(2.60)	(3.46)
Constant	0.457***	0.436***
	(9.68)	(11.26)
N	236	236
R^2	0.0318	0.0567
R^2_{adj}	0.0277	0.0527

Model derivations

In this section, we provide further derivations for the model presented in Section 3.2. First, we derive the cut-off rates for lenders. The cut-off rate $\hat{b}_t^k$ that makes a lender of type k indifferent between using a market or a limit order solves:

$$E_t\left[\pi(a_t^*)\right] = \pi(\hat{b}_t^k) \tag{I.3}$$

$$P_t^k(a_t^*)\left[a_t^* - \mu_0 - v\right] + \left(1 - P_t^k(a_t^*)\right)\left[r_{DF} - \mu_0 - v\right] = \hat{b}_t^k - \mu_0 - v, \tag{I.4}$$

where the left-hand side is the expected profit from posting a limit order at a_t^* and the right-hand side is the profit of using a market order that is executed immediately at $\hat{b}_t^k$. Solving for the cut-off borrowing rate $\hat{b}_t^k$ yields Equation (6) in the paper. The execution probabilities for the lender are presented in Table I.2.

Table I.2: Execution probability lender

$P_t^k(a) = 0$	if $a > \hat{a}_{t+1}^H$
$P_t^k(a) = \frac{1}{2}\theta\tau_k$	if $\hat{a}_{t+1}^L > a \geq \hat{a}_{t+1}^H$
$P_t^k(a) = \frac{1}{2}\theta\tau_k + \frac{1}{2}(1-\theta)\tau_k = \frac{1}{2}\tau_k$	if $\hat{a}_{t+1}^L \geq a$

In order to derive the equilibrium rates, we need to solve the following equations for bid and ask rates, which follow from Equations (5) – (7) in the paper:

$$\begin{aligned}
\hat{a}^H &= P^H(\hat{b}^H)\hat{b}^H + \left(1 - P^H(\hat{b}^H)\right) r_{MLF} = P^H(\hat{b}^L)\hat{b}^L + \left(1 - P^H(\hat{b}^L)\right) r_{MLF} \\
\hat{b}^H &= P^H(\hat{a}^H)\hat{a}^H + \left(1 - P^H(\hat{a}^H)\right) r_{DF} = P^H(\hat{a}^L)\hat{a}^L + \left(1 - P^H(\hat{a}^L)\right) r_{DF} \\
\hat{a}^L &= P^L(\hat{b}^H)\hat{b}^H + \left(1 - P^L(\hat{b}^H)\right) r_{MLF} = P^L(\hat{b}^L)\hat{b}^L + \left(1 - P^L(\hat{b}^L)\right) r_{MLF} \\
\hat{b}^L &= P^L(\hat{a}^H)\hat{a}^H + \left(1 - P^L(\hat{a}^H)\right) r_{DF} = P^L(\hat{a}^L)\hat{a}^L + \left(1 - P^L(\hat{a}^L)\right) r_{DF}
\end{aligned}$$

Next, we solve for $\hat{a}^H$, $\hat{b}^H$, $\hat{a}^L$, and $\hat{b}^L$ to obtain Equations (8) – (11) in the paper.

$$\begin{aligned}
\hat{a}^H &= \frac{\tau_H\theta}{2}\left(\frac{\tau_H\theta}{2}\hat{a}^H + \left(1 - \frac{\tau_H\theta}{2}\right) r_{DF}\right) + \left(1 - \frac{\tau_H\theta}{2}\right) r_{MLF} \\
&= \frac{\tau_H^2\theta^2}{4}\hat{a}^H + \frac{\tau_H\theta}{2} r_{DF} - \frac{\tau_H^2\theta^2}{4} r_{DF} + \left(1 - \frac{\tau_H\theta}{2}\right) r_{MLF} \\
&= \frac{1}{1 - \frac{\tau_H^2\theta^2}{4}}\left(\frac{\tau_H\theta}{2} r_{DF} - \frac{\tau_H^2\theta^2}{4} r_{DF} + r_{MLF} - \frac{\tau_H\theta}{2} r_{MLF}\right) \\
&= \frac{\frac{\tau_H\theta}{2}}{1 + \frac{\tau_H\theta}{2}} r_{DF} + \frac{1}{1 + \frac{\tau_H\theta}{2}} r_{MLF}
\end{aligned}$$

$$\begin{aligned}
\hat{b}^H &= \frac{\tau_H\theta}{2}\left(\frac{\tau_H\theta}{2}\hat{b}^H + (1-\frac{\tau_H\theta}{2})r_{MLF}\right) + (1-\frac{\tau_H\theta}{2})r_{DF} \\
&= \frac{\tau_H^2\theta^2}{4}\hat{b}^H + \frac{\tau_H\theta}{2}r_{MLF} - \frac{\tau_H^2\theta^2}{4}r_{MLF} + (1-\frac{\tau_H\theta}{2})r_{DF} \\
&= \frac{1}{1-\frac{\tau_H^2\theta^2}{4}}\left(\frac{\tau_H\theta}{2}r_{MLF} - \frac{\tau_H^2\theta^2}{4}r_{MLF} + r_{DF} - \frac{\tau_H\theta}{2}r_{DF}\right) \\
&= \frac{\frac{\tau_H\theta}{2}}{1+\frac{\tau_H\theta}{2}}r_{MLF} + \frac{1}{1+\frac{\tau_H\theta}{2}}r_{DF}
\end{aligned}$$

$$\begin{aligned}
\hat{a}^L &= \frac{\tau_L}{2}\left(\frac{\frac{\tau_L}{2}}{1+\frac{\tau_L}{2}}r_{MLF} + \frac{1}{1+\frac{\tau_L}{2}}r_{DF}\right) + \left(1-\frac{\tau_L}{2}\right)r_{MLF} \\
&= \frac{1}{1+\frac{\tau_L}{2}}r_{MLF} + \frac{\frac{\tau_L}{2}}{1+\frac{\tau_L}{2}}r_{DF}
\end{aligned}$$

$$\begin{aligned}
\hat{b}^L &= \frac{\tau_L}{2}\left(\frac{\tau_L}{2}(b_L) + \left(1-\frac{\tau_L}{2}\right)r_{MLF}\right) + \left(1-\frac{\tau_L}{2}\right)r_{DF} \\
&= \frac{\left(\frac{\tau_L}{2}\left(1-\frac{\tau_L}{2}\right)r_{MLF}\right) + \left(1-\frac{\tau_L}{2}\right)r_{DF}}{1-\frac{\tau_L^2}{4}} \\
&= \frac{\frac{\tau_L}{2}}{1+\frac{\tau_L}{2}}r_{MLF} + \frac{1}{1+\frac{\tau_L}{2}}r_{DF}
\end{aligned}$$

Table I.3 summarizes the cut-off prices and limit orders that banks are indifferent to paying/receiving.

Table I.3: Market order cut-offs and limit orders

Type	Market order cut-off	Indifferent limit orders
High borrower	$\hat{a}^H$	$\hat{b}^H$, $\hat{b}^L$
High lender	$\hat{b}^H$	$\hat{a}^H$, $\hat{a}^L$
Low borrower	$\hat{a}^L$	$\hat{b}^H$, $\hat{b}^L$
Low lender	$\hat{b}^L$	$\hat{a}^H$, $\hat{a}^L$

In order to compute the possible bid/ask spreads, we compute all four rate combinations from Equations (8) – (11) in the paper:

$$\begin{aligned}
\hat{a}^H - \hat{b}^H &= \left(\frac{\frac{\tau_H\theta}{2}}{1+\frac{\tau_H\theta}{2}}r_{DF} + \frac{1}{1+\frac{\tau_H\theta}{2}}r_{MLF}\right) - \left(\frac{\frac{\tau_H\theta}{2}}{1+\frac{\tau_H\theta}{2}}r_{MLF} + \frac{1}{1+\frac{\tau_H\theta}{2}}r_{DF}\right) \\
&= \frac{2-\tau_H\theta}{2+\tau_H\theta}r_{MLF} - \frac{2-\tau_H\theta}{2+\tau_H\theta}r_{DF} \\
&= \frac{2-\tau_H\theta}{2+\tau_H\theta}(r_{MLF} - r_{DF}) \\
&= \frac{4-\tau_L\tau_H\theta+2(\tau_L-\tau_H\theta)}{(2+\tau_L)(2+\tau_H\theta)}(r_{MLF} - r_{DF})
\end{aligned}$$

$$\begin{aligned}\hat{a}^L - \hat{b}^L &= \left(\frac{1}{1+\frac{\tau_L}{2}} r_{MLF} + \frac{\frac{\tau_L}{2}}{1+\frac{\tau_L}{2}} r_{DF}\right) - \left(\frac{\frac{\tau_L}{2}}{1+\frac{\tau_L}{2}} r_{MLF} + \frac{1}{1+\frac{\tau_L}{2}} r_{DF}\right) \\ &= \frac{2-\tau_L}{2+\tau_L}(r_{MLF} - r_{DF}) \\ &= \frac{4-\tau_L\tau_H\theta - 2(\tau_L - \tau_H\theta)}{(2+\tau_L)(2+\tau_H\theta)}(r_{MLF} - r_{DF})\end{aligned}$$

$$\begin{aligned}\hat{a}^H - \hat{b}^L &= \left(\frac{\frac{\tau_H\theta}{2}}{1+\frac{\tau_H\theta}{2}} r_{DF} + \frac{1}{1+\frac{\tau_H\theta}{2}} r_{MLF}\right) - \left(\frac{\frac{\tau_L}{2}}{1+\frac{\tau_L}{2}} r_{MLF} + \frac{1}{1+\frac{\tau_L}{2}} r_{DF}\right) \\ &= \left(\frac{2}{2+\tau_H\theta} - \frac{\tau_L}{2+\tau_L}\right) r_{MLF} - \left(\frac{2}{2+\tau_L} - \frac{\tau_H\theta}{2+\tau_H\theta}\right) r_{DF} \\ &= \frac{4-\tau_L\tau_H\theta}{(2+\tau_L)(2+\tau_H\theta)}(r_{MLF} - r_{DF})\end{aligned}$$

$$\begin{aligned}\hat{a}^L - \hat{b}^H &= \left(\frac{1}{1+\frac{\tau_L}{2}} r_{MLF} + \frac{\frac{\tau_L}{2}}{1+\frac{\tau_L}{2}} r_{DF}\right) - \left(\frac{\frac{\tau_H\theta}{2}}{1+\frac{\tau_H\theta}{2}} r_{MLF} + \frac{1}{1+\frac{\tau_H\theta}{2}} r_{DF}\right) \\ &= \frac{4-\tau_L\tau_H\theta}{(2+\tau_L)(2+\tau_H\theta)}(r_{MLF} - r_{DF})\end{aligned}$$

The four spreads have different probabilities of occurrence, depending on θ:

1. $[a^H, b^H]$ arises if H bank follows H bank. The probability is θ^2.
2. $[a^L, b^L]$ arises if L bank follows L bank. The probability is $(1-\theta)^2$.
3. $[a^L, b^H] = [a^H, b^L]$ arises if L bank follows H bank or vice versa. The probability is $2(1-\theta)\theta$.

Alternative first and second-stage regression models

Using the residuals from Equation (16) as proxy for funding liquidity risk is a conservative measure because some of the controls may capture parts of the variation in banks' funding liquidity risk. In addition, balance sheet data and CDS spreads are not available for all banks, thereby reducing the number of observations. Against this background, in this section, we test whether our results are robust to changing the composition of control variables and allowing for a bigger sample of banks.

Table I.4 presents first- and second-stage regression results for different specifications. In Column (1) and (2), we drop CDS spreads from the matrix of control variables. This enables us to extend the number of observations to 27,801. In Column (3) and (4), we drop $TradeTime$ from the matrix of controls because it might eliminate some of the variation in liquidity risk to the extent that it captures the time of arrival of banks in the market. The later a bank arrives, the more time-sensitive a funding shock could be, as markets tend to be closing soon. However, $TradeTime$ only measures the execution time of a trade. In particular in the case of limit orders, the execution time of a trade can be far away from the market arrival of a bank. Since the execution time of trades is important—particularly for the second stage—we decide to include it in our matrix of controls in our baseline specification in the paper. In Column (5) and (6), we add bank fixed effects to the first-stage model. Bank fixed effects enable us to control for time-invariant unobserved heterogeneity. For example, there might be institutional differences across banks that affect their order choice but are unrelated to funding liquidity risk. The results remain qualitatively the same in all specifications.

Table I.4: Alternative first- and second stage specifications

Table I.4 presents alternative specification for the first and second stage regression models. *LiquidityRisk* is our proxy for the idiosyncratic funding liquidity risk of banks, as presented in Section 4.3. All models are estimated via least square dummy variable (LSDV) regressions, including bank and day fixed effects. *Experience* is measured by the cumulative number of trading days in logs. $Volume$, $TotalAssets$, and CDS spreads are also in logs. t-statistics are shown in parentheses. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	(1) MOS	(2) r^e	(3) MOS	(4) r^e	(5) MOS	(6) r^e
LiquidityRisk		1.380***		1.957***		2.005***
		(10.82)		(9.13)		(10.62)
Volume	-0.0826***	0.0188	-0.0595***	0.290***	-0.0529***	0.146**
	(-7.06)	(0.41)	(-6.12)	(3.61)	(-10.85)	(2.14)
TradeTime	-0.00673	-0.196***			0.00772	-0.291***
	(-1.02)	(-5.75)			(1.16)	(-8.68)
Experience	0.0123	-0.110	0.0247	-0.119	0.0345*	-0.0577
	(0.92)	(-0.94)	(1.32)	(-0.56)	(1.78)	(-0.30)
Size	0.0102	0.767*	0.0524	1.471	-0.0439	1.306
	(0.80)	(1.95)	(1.37)	(1.35)	(-1.04)	(1.25)
ROAA	-0.00972	0.0920	-0.0308	0.314**	0.00105	0.225*
	(-0.43)	(1.16)	(-0.87)	(2.39)	(0.06)	(1.72)
Leverage	-0.00206	0.0278	-0.00433	0.0301	0.00119	0.0289
	(-0.51)	(1.30)	(-1.39)	(1.12)	(0.26)	(1.19)
CDS			0.0169	-0.0706	-0.0107	-0.0495
			(0.93)	(-0.89)	(-0.81)	(-0.85)
Constant	0.959***	-0.954	0.318	-9.818	0.775*	-4.951
	(5.28)	(-0.48)	(1.39)	(-1.49)	(2.07)	(-0.79)
Bank/Day FE	no/no	yes/yes	no/no	yes/yes	yes/yes	yes/yes
NT	27,801	27,801	11,486	11,486	11485	11,485
R^2	0.0533	0.197	0.0576	0.248	0.161	0.267
Adj. R^2	0.0531	0.111	0.0571	0.0513	0.159	0.0758

t statistics in parentheses

* $p < .1$, ** $p < .05$, *** $p < .01$

Validity tests

Table I.5 presents the contingency matrix corresponding to the logistic regression in Section 4.3. $LiquidityRisk$ is our measure of liquidity risk and $Switch$ indicates if a bank switches from lending to borrowing on a given day. We use the switching between borrowing and lending as a proxy for liquidity shocks and hence, we expect banks to have a higher liquidity risk on days when they switch. In line with this expectation, Table I.5 shows that the likelihood of having a positive liquidity risk is considerably higher on switching days ($\frac{16,272}{37,127} = 0.44$ when $Switch = 0$ vs. $\frac{560}{876} = 0.64$ when $Switch = 1$).

Table I.5: Validity test of $LiquidityRisk$: Contingency table

Table I.5 presents a contingency matrix of $LiquidityRisk$ when changing or not changing the direction of trading. A trade is categorized as switching ($Switch = 1$) if a bank switches from lending to borrowing.

	$Switch = 0$	$Switch = 1$	Total
$LiquidityRisk \leq 0$	20,855	316	21,171
$LiquidityRisk > 0$	16,272	560	16,832
Total	37,127	876	38,003

Table I.6 and Table I.7 present the contingency matrix and logistic regression results for lenders. In case of lenders, a trade is categorized as switching if a bank switches from borrowing to lending. The results are similar to borrowers. The likelihood of having a positive liquidity risk is considerably higher on switching days ($\frac{4,738}{12,241} = 0.39$ when $Switch = 0$ vs. $\frac{124}{196} = 0.63$ when $Switch = 1$). Lenders switch slightly less often than borrowers, but the odds ratio of having a positive liquidity risk increases by 2.7 if they switch.

Table I.6: Validity test of $LiquidityRisk$: Contingency table (lender)

Table I.6 shows a contingency matrix of $LiquidityRisk$ when changing or not changing the direction of trading. A trade is categorized as switching ($Switch = 1$) if a bank switches from borrowing to lending.

	$Switch = 0$	$Switch = 1$	Total
$LiquidityRisk \leq 0$	7,503	72	7,575
$LiquidityRisk > 0$	4,738	124	4,862
Total	12,241	196	12,437

Table I.7: Validity test of *LiquidityRisk*: Logistic regression (lender)

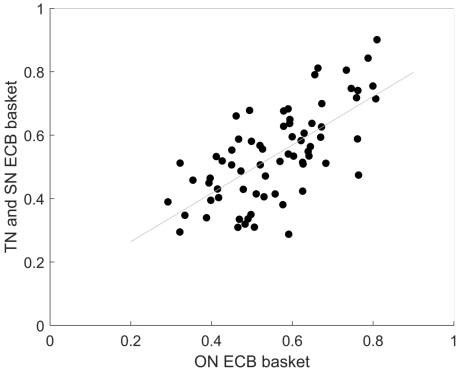
Table I.7 presents the results of a logistic regression of $LiquidityRisk > 0$ on the dummy *Switch*, which takes the value 1 on days on which a bank enters the market as borrower and later switches to lending. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	$LiquidityRisk > 0$	Odds Ratio
Switch	1.003***	2.727***
	(6.72)	(6.72)
Constant	−0.460***	
	(−24.77)	
N	12,437	12,437

Additional figures

Figure I.1: Performance across tenors

Figure I.1 presents the performance of banks across different tenors. The y-axis plots the relative frequency of banks when trading TN and SN repos. The x-axis plots the performance for ON repos. The relative frequency ranges from 0 to 1; a value of 0.5 means a bank pays more than the daily average repo rate in 50% of its trades. Every dot represents one bank. Outperforming the market means having a relative frequency greater than 0.5 when borrowing and smaller 0.5 when lending.



Curriculum Vitae

Alexander Bechtel - CV

Educational Background

2016 – 2021	**University of St. Gallen, Switzerland** PhD in Finance
2013 – 2016	**University of St. Gallen, Switzerland** Master (M.A.) in Quantitative Economics & Finance
2009 – 2013	**University of Bayreuth, Germany** Bachelor (B.Sc.) in Economics Bachelor (B.A.) in International Economics & Development

Academic Exchanges and Visiting Positions

2018	**Stanford University, USA** Visiting Student Researcher, Host: Arvind Krishnamurthy
2011 – 2012	**EDHEC Business School, France** Exchange Student

Work Experience

2021 –	**Deutsche Bank, Switzerland** Head of Distributed Ledger Technology and Digital Asset Strategy
2016 – 2021	**University of St. Gallen, Switzerland** Research and Teaching Assistant
2017 – 2018	**European Central Bank, Germany** External Consultant