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Central Bank–Driven Mispricing[☆]

Loriana Pelizzon[a], Marti G. Subrahmanyam[b], Davide Tomio[c,*]

[a] Goethe University Frankfurt & Ca' Foscari University of Venice, Theodor-W.-Adorno-Platz 3, 60323 Frankfurt am Main, Germany
[b] Leonard N. Stern School of Business & NYU Shanghai, New York University, 44 West Fourth Street, New York, NY 10012, USA
[c] Darden School of Business, University of Virginia, 100 Darden Boulevard, Charlottesville, VA 22903, USA

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ABSTRACT

We explore whether Quantitative Easing (QE) negatively affected the functioning of the treasury market. Focusing on the arbitrage between European sovereign bonds and their futures contracts, we show that the scarcity of treasuries created by QE led to a disconnect between the prices of identical assets. We identify three channels: reduced bond market liquidity, increased funding costs in the repo market, and a higher cost of carry. A change in a policy instrument allows us to identify scarcity as the main driver and rule out alternatives, such as balance sheet costs. Our results extend to other arbitrage relations involving treasuries.

1. Introduction

Following the Great Recession, central banks engaged in Quantitative Easing (QE), mainly through large-scale purchases of government debt. These interventions were effective in lowering treasury yields (D'Amico et al., 2012; D'Amico and King, 2013; Song and Zhu, 2018), operating through, among others, the channel of scarcity: As QE reduces the supply of treasuries, their prices increase, since investors have investment needs that can only be satisfied by safe assets (Krishnamurthy and Vissing-Jorgensen, 2013).

Policy makers have hypothesized a possible tension inherent to a central bank's decision to engage in QE (Bernanke, 2012; Cœuré, 2015): The reduction in treasury yields may come at the cost of a deterioration in market functioning and a suppression of the price discovery mechanism. The goal of much of the previous literature has been to show the effect of QE on asset prices. In this paper, we provide the first empirical evidence that the scarcity that followed the QE purchases by the European Central Bank (ECB) negatively affected the quality of the market for treasuries. Specifically, we show that QE impeded the arbitrage mechanism: Scarcity limited the ability of arbitrageurs to ensure that prices across markets for interest rates were closely aligned by increasing the transaction, funding, and carry costs they face.

We obtain our results in three steps. We focus our analysis on a textbook example of arbitrage — that between cash treasuries and their

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* Corresponding author.
E-mail addresses: pelizzon@safe.uni-frankfurt.de (L. Pelizzon), msubrahm@stern.nyu.edu (M.G. Subrahmanyam), tomiod@darden.virginia.edu (D. Tomio).

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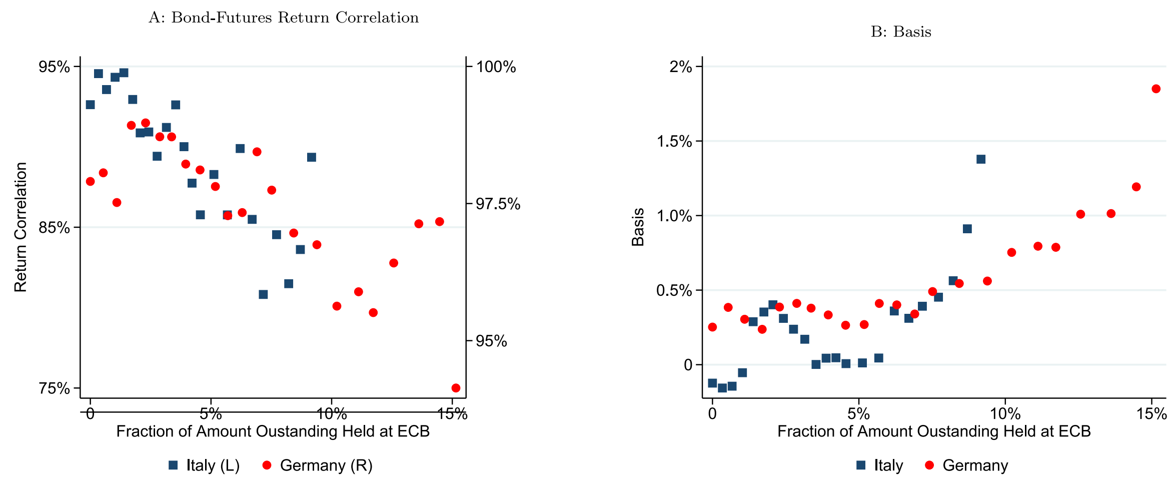

Fig. 1. Central Bank Holdings of Sovereign Bonds and the Futures-Bond Arbitrage: This figure shows the time series of sovereign bonds holdings by the ECB as a fraction of their outstanding amount and measures of the deviation between prices of bonds and futures. Panels A and B show $Basis_{it}$, the annualized return from buying a futures and shorting the CTD bond, in the absence of trading and funding costs, at a daily frequency. Panels C and D show the daily 1-min return correlation between futures contracts and deliverable bonds, $Corr_{it}$. The dashed line represents the amount of bonds held at the ECB as a fraction of the total amount of bonds outstanding (on the right axes). Data on bond purchases are obtained from the ECB and data on the amount of bond outstanding are obtained from the National Central Banks. Data on bond prices and characteristics are obtained from MTS, data on repo transactions are obtained from MTS and BrokerTec, and futures data are obtained for the Eurex market via Thomson Reuters. The dashed vertical line marks the implementation of the cash-collateralized securities lending facility.

futures contracts — and measure impediments to the arbitrage mechanism in two ways, using return correlations and price differential. We calculate these quantities for the most liquid, long-term futures on German and Italian debt. We plot these measures for varying levels of bond holdings by the ECB in Fig. 1, which gives a preview of our first set of findings.

First, we find a positive association between increased ECB bond holdings and impediments to price discovery: As central banks holdings grew from 0% to 15% of the outstanding amount, the return correlation between assets with virtually identical cash flows decreased from 99% to 94% (95% to 81%) for Germany (Italy), a decrease of seven (eight) pre-QE standard deviations, indicating a significant divergence between bonds and futures prices. This decrease in correlation hinders market participants' ability to hedge. For example, the one-day 5%-expected shortfall of a €1 million bond portfolio that is fully hedged with a futures contract would have increased by 145%, from €567 to €1389 (95%, from €1268 to €2472). Similarly, the price differential between futures and bonds increased from 0% for both countries to 1.8% and 1.5% for Germany and Italy, respectively.

Second, we show that the disconnect between bonds and futures is a consequence of the central bank's impact on three costs faced by arbitrageurs: (i) transaction costs, (ii) security borrowing costs, and (iii) the cost of carry. Using the bond's bid–ask spread as a measure of illiquidity, we show that a 10% increase in the stock of bonds held by the ECB increased the bid–ask spread by €1.6 cents, a 25% increase over the pre-QE average bid–ask spread. We measure the cost of borrowing a bond by its repo "specialness", that is, by how large an interest rate a cash lender is willing to forego to borrow a specific asset, and show that a 10% increase in ECB's bonds holdings increased specialness by 28 bp, a five-fold increase over the before-QE specialness of 5 bp. Finally, we show that the slope of the term structure of specialness and repo volatility, which capture the costs of carry of an arbitrage transaction, increased significantly as a consequence of QE. These costs positively predict the disconnect between bond and futures prices, explaining 54%–65% of its variation.

Third, we demonstrate that our results are driven by scarcity using an exogenous shock based on a policy change. A natural alternative hypothesis is that dealers' balance sheet constraints affected the cost for the trade we consider, similar to what Fleckenstein and Longstaff (2020) and Du et al. (2018) show for the US futures-bond basis and covered interest rate parity, respectively. Using a balance sheet usage costs measure, based on unsecured-loan turn-of-the-year premium (Fleckenstein and Longstaff, 2020), we find that, while balance sheet constraints may have contributed, they were not the main driver of the mispricing dynamics we observe.

We identify scarcity as the principal channel by considering the implementation in 2016 of a cash-collateralized securities lending facility (CCSLF), whereby the ECB reduced asset scarcity by lending out its bond holdings against cash (Arrata et al., 2020; Roh, 2022). We show that the CCSLF resulted in an easing of the limits to arbitrage and an improvement in the functioning of treasury markets. Prior security lending efforts by national central banks were asset-collateralized and, thus, did not increase the aggregate supply of securities available for lending.

In our main analyses, we focus on the arbitrage mechanism between cash treasuries and their futures contracts. This is an ideal setting: the two legs of the trade are almost perfectly offsetting, and allow the trader to be fully hedged with a single transaction; the trades rely on firm quotes and are centrally cleared, leading to minimal execution- and counterparty-risk; the pricing relationship is a textbook case of arbitrage, which is obtained under minimal assumptions.

The QE-driven frictions we document, however, are common to any arbitrage trade that involves shorting cash sovereign bonds, not just that between bonds and futures. We show that our findings extend to term structure arbitrage trades, using deviations from a fitted yield curve (Hu et al., 2013), and the swap spread (Klingler and Sundaresan, 2019). As a counterfactual, we show that arbitrage trades only involving treasury derivatives (futures option put–call parity), which were not made scarce by QE, do not display signs of impediments to arbitrage.

The inefficiencies we document are a prime concern for central bankers, as the implementation of the CCSLF suggests. The ECB states that its QE operations must obey "the concept of market-neutrality[, that is,] while we do want to affect prices, we do not want to suppress the price discovery mechanism" (Cœuré, 2015). Similarly, the Federal Reserve System listed impairments to market liquidity and price discovery as a cost of continuing its Large-scale Asset Purchases (Bernanke, 2012). Our finding that QE impaired price discovery, but that the CCSLF improved market quality provides a guide on how to effectively implement QE, modulating scarcity to affect yields while maintaining market functioning.

It is in the policy makers' interest to ensure that market participants agree on the correct interest rate level, and also for the market for interest rates to be informative. Disagreement on monetary policy affects investment and consumption (Baker et al., 2016; Ehling et al., 2018). For market participants, uncertainty on the shape of the term structure translates into increased capital at risk, as the €10 trillion outstanding Euro-zone sovereign bonds are widely used as collateral. Finally, a divergence between interest rates and instruments designed to replicate them hurts market participants' ability to effectively hedge their interest rate exposure and indicates that monetary policy may be inefficiently transmitted across fixed income markets (Ballensiefen et al., 2023; Eisenschmidt et al., 2023).

The initial implementation of the CCSLF demonstrates that central banks already possess an effective tool to alleviate the impairment of market functioning that accompanies asset scarcity resulting from QE. Our empirical results point to a clear policy recommendation in this direction: the ECB should adjust the supply of safe assets it lends against cash to improve market functioning as and when the need arises. This adjustment can be achieved by increasing the overall and institution-specific security borrowing limits and/or by calibrating the pricing of its facilities. Thus, we propose that central banks consider their securities lending facilities as a second lever in their QE toolbox, aiming to contain the market-quality consequences that arise from the other lever, the outright purchases of bonds.

We describe the details of the ECB's QE intervention and the data sources we employ in Section 2. Section 3 presents the arbitrage trade we focus on, and shows that it is not profitable, prior to the QE. In Section 4, we show the effect that the QE had on the pricing relation between cash treasury and futures contracts and on the frictions to arbitrage in fixed-income markets. In Section 5 we use a policy-based shock and counterfactuals to show that scarcity drives our results. We present extensions of our analysis in Section 6 and a general discussion of our results in Section 7. We conclude in Section 8.

Literature review

The effect of unconventional monetary policy interventions on the price of targeted assets has been extensively investigated, in the context of the purchases by the Federal Reserve (Gagnon et al., 2011; Krishnamurthy and Vissing-Jorgensen, 2011; D'Amico et al., 2012; D'Amico and King, 2013; Bauer and Rudebusch, 2014; Song and Zhu, 2018), the ECB (Eser and Schwaab, 2016; Ghysels et al., 2016; Krishnamurthy et al., 2017; Koijen et al., 2021), and the Bank of England (Joyce et al., 2011; Christensen and Rudebusch, 2012).[1]

A new strand in the literature has focused on how QE affects treasury market liquidity (Pelizzon et al., 2016; De Pooter et al., 2018; Kandrac, 2018; Schlepper et al., 2020; Christensen and Gillan, 2022), and, most recently, the pricing of repo transactions (D'Amico et al., 2018; Arrata et al., 2020; Corradin and Maddaloni, 2020; Roh, 2022). We contribute to the literature by showing that these unintended consequences of QE impede the arbitrage mechanism at play in treasury markets, as they increase costs faced by arbitrageurs. We show that scarcity, one of the channels by which QE affects bond prices (D'Amico et al., 2012), can thus impede the pass-through of monetary policy from treasuries to other assets linked to them by arbitrage.

Pasquariello (2018) shows that government interventions in the foreign exchange market drive a wedge between American Depository Receipts and foreign stocks. We focus on the bond market, the direct object of the QE intervention and policy transmission.

Extensive recent work (Du et al., 2018, 2023; Anderson et al., 2021; Cenedese et al., 2021) has sought to establish the impact of regulatory (Boyarchenko et al., 2018) and balance sheet costs on pricing relations, primarily the covered interest rate parity. In the context of the futures-bond trade that we also consider, Fleckenstein and Longstaff (2020) show that the difference between observed and implied repo rates is a function of intermediaries' balance sheet costs. We contribute to this literature by proposing another threat to market functioning, that is the asset scarcity that follows central banks' unconventional monetary policies. While balance sheet costs certainly play a role, we show that they cannot explain the dynamics we observe, based on a measure developed by Fleckenstein and Longstaff (2020) and a policy change. To the extent that scarcity may drive balance sheet usage, our findings shed light on the determinants of these costs.

Our paper is related to the literature on the effects of institutional investors' demand on relative asset prices. Hazelkorn et al. (2022) consider the effect of futures investors on futures-spot bases and Klingler and Sundaresan (2019) the impact on pensions' demand on the swap spread. We show the impact of the ultimate price-insensitive institutional investor, a central bank, on the relative price of bonds. Lastly, we show its effect on the difference between derivatives-implied and observed risk-free rates (Fleckenstein and Longstaff, 2020; Van Binsbergen et al., 2022).

2. Institutional background and data

In this study, we employ high frequency data on the prices of Euro-zone sovereign bonds and futures contracts. We analyze the 2013–2017 period, which encompasses three years of QE, 2015–2017, and two control years. We focus on contracts written on the Italian and German treasuries. Futures contract are traded for two other Euro-zone countries, France and Spain, but we do not include them in our analysis, as their markets are significantly less developed and liquid: less than 1% of fixed-rate special repo transactions employ French treasuries as collateral, while more than 70% involve German or Italian bonds; further, futures on Spanish treasuries were first introduced in late 2015, i.e., after the control period.

In this section, we review the ECB's QE and the markets for bonds and futures contracts.

2.1. The ECB's bond purchasing program

In January 2015, the ECB announced a public sector purchase programme (PSPP), whereby it would purchase treasury bonds for over a year, beginning on March 9, 2015, with an expected balance sheet expansion of more than €1 trillion. The scale, scope, and duration of the PSPP was unprecedented in the ECB's history.

The program was scheduled to last up to September 2016, but was prolonged multiple times and ultimately suspended in 2018. The program consists of outright purchases at the rate of €50 billion a month. The pace was increased to €80 billion between April 2016 and March 2017. The monthly purchases are allocated across all Euro-zone countries according to their participation in the ECB's capital, a function of the country's population and GDP (Koijen et al., 2021). The ECB does not disclose details of the purchase process, but reports that bond purchases took place via direct acquisition in the secondary market.

In our analysis, we measure scarcity as the fraction of a country's treasury market held by the ECB.[2] We obtain from the ECB the aggregate amount of bonds purchased at a monthly frequency, at the country level. The dashed lines in Fig. 2 show ECB's monthly bond holdings as a fraction of their corresponding outstanding amounts for Germany and Italy. Each month, the ECB purchased, on average, €9 (13) billion worth of Italian (German) bonds. Section IA.1 of the Appendix shows monthly purchased amounts. After two years of QE, the ECB held €$9 \cdot 24 = 216$ (€$13 \cdot 24 = 312$) billion worth of Italian (German) bonds,

[1] See Joyce et al. (2012), Buraschi and Whelan (2016), and Borio and Zabai (2018) for extensive reviews of the literature.

[2] Bond purchases were conducted by the Eurosystem, that is, jointly by the ECB and the Euro-zone's national central banks. For simplicity, we refer to the securities as being purchased and held by the ECB.

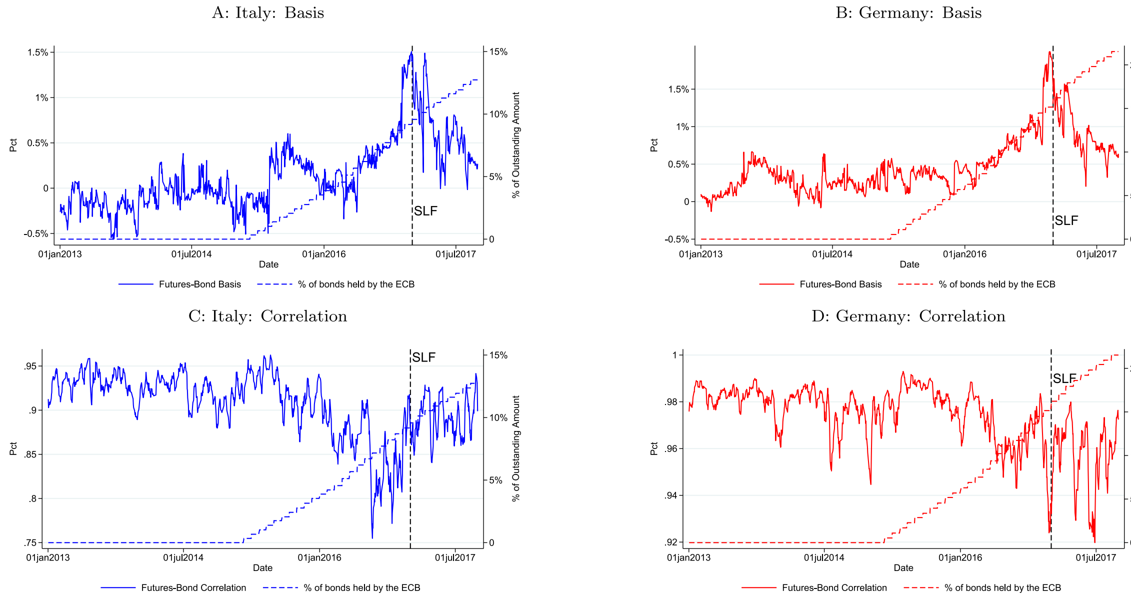

Fig. 2. Central bank holdings of sovereign bonds and the futures-bond arbitrage: This figure shows the time series of sovereign bonds holdings by the ECB as a fraction of their outstanding amount and measures of the deviation between prices of bonds and futures. Panels A and B show $Basis_{it}$, the annualized return from buying a futures and shorting the CTD bond, in the absence of trading and funding costs, at a daily frequency. Panels C and D show the daily 1-min return correlation between futures contracts and deliverable bonds, $Corr_{it}$. The dashed line represents the amount of bonds held at the ECB as a fraction of the total amount of bonds outstanding (on the right axes). Data on bond purchases are obtained from the ECB and data on the amount of bond outstanding are obtained from the National Central Banks. Data on bond prices and characteristics are obtained from MTS, data on repo transactions are obtained from MTS and BrokerTec, and futures data are obtained for the Eurex market via Thomson Reuters. The dashed vertical line marks the implementation of the cash-collateralized securities lending facility.

or about 12% (15%) of the €1.8 trillion (€2.1) outstanding.[3]

Shortly after the beginning of the PSPP, in April 2015, the ECB implemented a securities lending program, whereby market participants could borrow the purchased securities against bond-collateral in a repo/reverse-repo matched transaction. In order to counteract potential scarcity on the bond market (Cœuré, 2017; Jank and Mönch, 2018), the ECB initiated the CCSLF on December 15, 2016, whereby it began lending securities on a cash-collateralized basis. This repo transaction would take place at a rate equal to the minimum between the deposit facility rate minus 30 basis points and the prevailing market repo rate. We employ this policy change as a shock to scarcity in Section 5.1.

2.2. The cash and repo bond markets

We obtain price and volume data for the cash sovereign bonds from the MTS Group. The MTS trading system is an automated, quote-driven electronic limit order interdealer market (Pelizzon et al., 2016). The dataset provides the most complete representation of the Eurozone sovereign bond market: millisecond-stamped quotes, orders, and transactions.

To study the determinants of the mispricing between bonds and futures, we need to measure the costs of funding arbitrage positions, the cost of borrowing/shorting a bond. We obtain from Bloomberg the rate for a repo transaction for the general collateral (GC) Pooling ECB EXTended Basket, and use it to proxy for the collateralized borrowing rate (Mancini et al., 2015). We measure the cost of borrowing a specific bond by the rate for special repo transactions that took place on the two largest platforms, MTS Repo, operated by the MTS Group, and BrokerTec, of the NEX Group (Arrata et al., 2020).

[3] The ECB purchased both central and local government bonds. Since it did so proportionally to their outstanding amount, the measure of scarcity we employ, based on total public debt, is fitting for both. Local bonds make up a quarter of German public debt and only a minuscule amount of Italian public debt.

2.3. The futures market

A government bond futures is an exchange-traded instrument, a contract for the seller to deliver a bond to the buyer by a delivery date. Upon delivery, the buyer pays a price agreed upon on the date of the trade. The seller can deliver any bond from a basket of deliverable obligations, i.e., coupon-bearing bonds issued by the Italian (German) government, with a remaining life of 8.5 to 11 (10.5) years and an original maturity of up to 16 (11) years.

To obviate the seller's incentive to short-change the buyer by delivering a bond that is substantially cheaper than the others, the futures contract buyer will only pay a proportion of the agreed-upon futures price, specific to the bond that is actually delivered, the bond's conversion factor. Appendix A details the workings of conversion factors.

While conversion factors even out the price differences across deliverable bonds, a specific bond can be identified as the one that the futures seller is most likely to deliver. This bond is the cheapest between those that are deliverable, after taking into account its price and conversion factor, and is referred to as the cheapest-to-deliver (CTD) bond. A host of factors determines which of the deliverable bonds is CTD, including whether the bond is in abundant supply, and the shape of the yield curve. In general, if interest rates are low, the shortest duration bond is the CTD (Merrick et al., 2005).

The CTD bonds are clearly identified in our sample, having the lowest basis for almost the entire life of a contract. The median frequency, across contracts, that CTD has the lowest basis is 99.72% (99.84%) of the time for Italy (Germany). We present details on the identification of the CTD bond in Appendix A.

Our bond futures data include millisecond-stamped trades and quotes for long-term futures contracts traded on Eurex, an electronic limit order market. Futures contracts deliveries follow a quarterly basis: in March, June, September, and December. While contracts with up to nine months to delivery are traded at the same time, we focus on the nearest delivery, which is the most liquid contract. Our sample covers 20 contracts per country.

Descriptive statistics for all variables employed in our analysis are presented in Table B.1 and Appendix B.

3. The disconnect between bond and futures prices

To measure the disconnect between cash bond and derivative markets, we consider two measures. First, the return of a strategy of shorting the bond and going long the futures. The steps of the arbitrage strategy, at trade time t for a contract with delivery date T, are:

At time t	At time T
Borrow CTD at repo rate $r_{t,T}$	Receive CTD from futures seller
Sell CTD at price B_t	Deliver CTD to repo buyer
Long futures contract at price F_t	

Taking into account the conversion factor, coupons, and the gains from the repo transaction, we calculate the basis, i.e., the difference between the price of the CTD bond and a replicating portfolio made up of the futures contract, for day t and trading minute m:

$$Basis_{m,t} = \frac{1}{100}\left[\underbrace{\left(B_{m,t} + A_{i,t+2}\right)\left(1 + \frac{T-(t+2)}{360} r_{t,T}\right) - A_T}_{\text{Forward Bond Price}} - \underbrace{F_{m,t} \cdot CF}_{\text{Futures Equivalent Price}}\right]\left(\frac{T-t}{365}\right)^{-1} \quad (1)$$

where $B_{m,t}$ is the CTD bond's price and CF its conversion factor, $F_{m,t}$ the futures price, $\frac{T-(t+2)}{360}$ the term of the repo based on a $t+2$-day settlement, $r_{t,T}$ the reverse-repo rate (the arbitrageur lends cash and earns the repo rate), and A_{t+2} and A_T are coupons accrued by the trade settlement date and futures delivery, respectively.[4] We average the basis measure to obtain a daily estimate, $Basis_{it}$ for country i and day t. We use the near delivery contract until 20 days to delivery, when volume plummets, and the following contract thereafter.

We follow Hazelkorn et al. (2022) and normalize the basis by time-to-delivery, to be able to compare observations across- and within-contracts, and to capture the decay of the basis as delivery approaches. The price differential is obtained in euros per €100 of face value, thus the basis can be interpreted as the annualized return for going long a cash bond and short a futures contract. It can also be interpreted as $Basis_t \approx r_{t,T} - \hat{R}_{t,T}$, the difference between quoted and implied repo rate.[5] We use the latter as alternative dependent variable in Section 5.

The basis includes the option of delivering whichever bond is cheapest at delivery (Gay and Manaster, 1984; Kane and Marcus, 1986; Boyle, 1989; Hemler, 1990). This option is valuable if yields are close to 6% (Johnson et al., 2017), a much higher level than the 2015–2017 average of 0.2% (1.7%) for Germany (Italy), making the optionality negligible. Nonetheless, we ease the concern that the optionality affects our conclusions by normalizing the basis by time-to-delivery, which addresses the option's time decay. Moreover, following the application by Merrick et al. (2005) of the switching option model by Margrabe (1978), we control for the volatility of the return differential between first and second CTD bond and their price ratio in which the option value increases.

Fig. 2 shows the time series of $Basis_t$ for Italian and German futures contracts, in Panel A and B, respectively. The fraction of all sovereign bonds held at the ECB is plotted as a dashed line. The figure illustrates our first finding: Prior to the QE, the market functioning was efficient. However, as the ECB reduced the bonds available to the public, the disconnect between the bond and futures contract increased substantially in the scarcity created by the ECB. The vertical line marks the date of the implementation of the CCSLF, which we study in Section 5.1: As the ECB reduced bonds' scarcity by lending them in exchange for cash, the disconnect between markets subsided.

$Basis_{it}$ is not the same as arbitrage profits. We calculate this measure using the midquote price of bonds, assuming the cash lent to borrow the bond is remunerated at the collateralized rate, Eurex's GC Pooling ECB EXTended rate, and that the overnight rate applies to the term repo. $Basis_{it}$, thus, includes the frictions faced by arbitrageurs: (i) transaction, (ii) security borrowing, and (iii) carrying costs. Our objective here is not to capture arbitrage profits, but rather to show that QE worsened these frictions, or limits to arbitrage.

Fig. 2 shows that, prior to the QE, the frictions included in the calculation were generally not large enough to cause a significant deviation in the prices of bonds and futures. In Section 4 we show that, as a result of the QE, the frictions increased to such a degree that the price discovery process was significantly impeded. In Section 5 we show the presence of arbitrage opportunities, once we compute $Basis_{it}$ net of these costs.

As a second measure of divergence between the bond market affected by QE and derivatives markets, we calculate the 1-min return correlation between the nearest futures contracts and an equally-weighted portfolio of the $NDel_{it}$ deliverable bonds, for country-i day-t:

$$Corr_{it} = Corr\left(\sum_{j=1}^{Ndel_{it}} \frac{\Delta B_{ijtm}/B_{ijtm}}{NDel_{it}}, \Delta F_{itm}/F_{itm}\right) \quad (2)$$

Unlike $Basis_{it}$, this measure of market functioning does not require us to identify a CTD bond nor to take a stance on the funding rate. As shown in Panels C and D of Fig. 2, $Corr_{it}$ indicates that the effectiveness of hedging a portfolio of long-term bonds with the futures contract decreased as QE-related scarcity increased, in alignment with $Basis_{it}$.

To show the effect of the ECB's purchases on the relation between bond and future prices, we regress $Basis_{it}$ and $Corr_{it}$ on ECB_{it}, a dummy that is one during QE, and zero otherwise, a country dummy DE_i, and year- and quarter-end dummies, as in Eq. (3):

$$Basis_{it} = \alpha + \beta_1 ECB_{it} + \beta_2 DE_{it} + \beta_3 QuarterEnd_t + \beta_4 YearEnd_t + \varepsilon_{it} \quad (3)$$

Our sample consists of one observation per day for the German and Italian futures contracts for each of the 1105 trading days in our sample period, for a total of 2209 observations. Standard errors are two-way clustered, at the country-delivery and date level. We report the results in Table 1.

In Specification 1, we show that the basis is negligible before the QE intervention. During the QE intervention, however, bond prices increased more than that of the futures contract and the basis turned positive, averaging around 50 bps, significant at the 1% level. To account for the time-varying dynamics of the ECB holdings in Fig. 2, we repeat the analysis and substitute the dummy ECB_{it} with $ECB^{\%}_{it}$, the fraction of sovereign bonds held at the ECB for country i on the last day of the month of day t. The results in Specification 2 are both statistically and economically significant: a 10% increase in bond holdings by the ECB increased the basis between bonds and futures by 46 bp. Specification 3 and 4 repeat the analysis using $Corr_{it}$ as dependent variable. Prior to QE, the bond-futures 1-min return correlation was 92%. During QE, it decreases by 2.4%, or 2.3% per every 10% increase in bond holdings. Correlation is on average higher for the German sample, as captured by DE_i, which is mostly due to the lower number of deliverables in German contracts.

[4] The inclusion of A_{t+2} and A_T accounts for coupons to be paid between the cash-leg settlement date and the delivery date. We assume that coupons that are paid-out are reinvested at the GC rate. We calculate the basis using intraday data to increase the precision of our estimates, rather than relying on noisier single-point, end-of-day quotes. It should be emphasized that the trade leads to an arbitrage only if the positions are held to delivery, as posited in our calculations.

[5] $Basis_{m,t} \approx \frac{B_{m,t}+A_{i,t+2}}{100}\left[r_{t,T} - \left(\frac{F_{m,t}\cdot CF + A_T}{B_{m,t}+A_{i,t+2}} - 1\right)\left(\frac{T-t}{365}\right)^{-1}\right] \approx r_{t,T} - \hat{R}_{t,T}$, holding with equality if bonds trade at par, coupons are zero, and cash and repo trades share settlement and day-count conventions.

Table 1
Futures-bond price disconnect and quantitative easing: This table reports the results for the regression of measures of interest rate market efficiency on variables capturing QE-driven scarcity. The dependent variable in Specifications 1 and 2 is $Basis_{it}$, the difference in pricing between sovereign futures contracts and underlying bonds, calculated as in Eq. (1), for country-i on day-t. A positive basis implies that bonds prices are higher than those for futures contracts. $Basis_{it}$ is calculated at a one-minute frequency and averaged to create a daily series. The dependent variable in Specification 3 and 4 is the daily, 1-min return correlation between a futures contract and an equally weighted portfolio of deliverable bonds, $Corr_{it}$. The explanatory variables are ECB_{it}, a dummy that equals one during the ECB's QE period and zero, otherwise, and $ECB^{\%}_{it}$, the fraction of bonds held at the ECB. We control for the nationality of the contract, with the dummy variable DE_i, and deterministic year-end and quarter-end effects. *, **, and *** indicate that parameters are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are clustered at the delivery-country and date level. The sample extends from January 2013 to September 2017, resulting in 1105 observations each for the two countries we consider, Germany and Italy. Bond (futures) data are from MTS (Eurex). Data on the European general collateral rates are from Bloomberg.

	(1) $Basis_{it}$	(2) $Basis_{it}$	(3) $Corr_{it}$	(4) $Corr_{it}$
Constant	−0.001**	0.000	0.918***	0.913***
	(−2.029)	(−0.297)	(223.504)	(173.885)
ECB_{it}	0.005***		−0.024***	
	(5.497)		(−4.024)	
$ECB^{\%}_{it}$		0.046***		−0.226***
		(5.336)		(−5.599)
DE_i	0.003***	0.002***	0.068***	0.073***
	(3.890)	(3.373)	(10.840)	(11.609)
$YearEnd_t$	0.003	0.003	−0.014	−0.014
	(1.010)	(1.205)	(−1.269)	(−1.553)
$QuarterEnd_t$	0.000	0.000	0.004	0.004
	(0.079)	(−0.100)	(1.031)	(1.190)
Adj. R^2	0.439	0.556	0.560	0.575
Obs	2209	2209	2195	2195

We investigate the channels through which the scarcity that followed ECB bond purchases increased the futures-bond basis in Section 4, where we show that QE increased the frictions involved in the arbitrage trade, and impeded the price discovery process in the market for interest rates. In Section 5, we return to the efficiency measures and show that scarcity affected them through and above its effect on arbitrage costs and use an exogenous policy change to identify scarcity as the main driver.

4. Quantitative easing and frictions

In a market with unlimited capital and no transaction costs, the impact of ECB purchases on bond prices would be reflected one-to-one in the derivatives markets. In the more realistic setting of a world with market frictions, however, QE operations may impair the functioning of markets, leading to sluggish price discovery and present impediments to the law of one price. The frictions we identify are those of liquidity and collateral availability, as outlined by ECB and FED (Bernanke, 2012; Cœuré, 2015).

We can re-write Eq. (1) (dropping the subscript m) to make explicit the costs it includes:

$$Basis_t = \frac{1}{100}\Bigg[\left(B_t^{Bid} + \frac{1}{2}BA_t + A_{i,t+2}\right)\left(1 + \frac{T-(t+2)}{360}\left(R_{t,T} + Specialness_{t,t+1} + SpecialnessSlope_{t,T}\right)\right) - A_T - F_t \cdot CF\Bigg]\left(\frac{T-t}{365}\right)^{-1}. \quad (4)$$

We decompose the bond mid-price B_t into the bid price at which the bond sale would take place, B_t^{Bid}, and the transaction cost $B_t - B_t^{Bid}$, which corresponds to half the bid–ask spread BA_t. Similarly, we decompose the repo rate $r_{t,T}$ into the special repo rate $R_{t,T}$ and $Specialness_{t,T} = r_{t,T} - R_{t,T}$. A bond's specialness is the opportunity cost, or foregone profit, from lending cash in a collateralized transaction to obtain that specific security, and should be zero in a frictionless market.[6] We can further decompose the repo trade specialness into an overnight component $Specialness_{t,t+1} = r_{t,t+1} - R_{t,t+1}$ and a term component, $SpecialnessSlope_{t,T} = Specialness_{t,T} - Specialness_{t,t+1} = (r_{t,T} - R_{t,T}) - (r_{t,t+1} - R_{t,t+1})$, capturing the costs of carry for holding the position for longer than a one-day period.

As scarcity worsens market liquidity (BA_t) and collateral availability ($Specialness_{t,t+1}$ and $SpecialnessSlope_{t,T}$), QE impedes the price discovery process. In Section 4.1, we analyze the illiquidity of the bond market. In Sections 4.2 and 4.3, we study the two components of the cost of obtaining bonds via repo transactions, $Specialness_t$ and $SpecialnessSlope_t$.

4.1. Quantitative easing and bond market liquidity

The issue of the overall effect of QE on market liquidity is ultimately an empirical one, as a comprehensive theoretical framework of how central bank asset purchases affect market liquidity is not available in the literature. Intuitively, there are two opposing forces at play: On the one hand, the presence of a price-insensitive buyer may increase liquidity, as sellers can readily find a buyer and liquidate their positions. On the other, the higher asset scarcity may increase dealers' capacity to extract rents and, thus, decrease market liquidity.

To highlight the tension between the two forces, we turn to standard market microstructure models to develop a framework to link asset purchases to the market liquidity provided by dealers. Following the taxonomy in the market microstructure literature, QE affects liquidity if it impacts inventory costs, search costs, or informational asymmetry costs. We hypothesize that it increases the first two costs, as informational costs are unlikely to play a significant role in the context of sovereign bonds.

In an inventory model à la (Amihud and Mendelson, 1980), asset purchases can be thought of as a parallel upward shift in the demand function faced by dealers, or as a reduction in demand elasticity (Koijen et al., 2021). In Section IA.2 of the Internet Appendix, we show that, regardless of which parametrization is used, QE results in an increase in the rent captured by the monopolistic market maker, who quotes larger bid–ask spreads. That is, the monopolist power of the dealer in the inventory model delivers that QE has a deleterious impact on market liquidity. The model is ambiguous regarding whether buyers and sellers are equally impacted. Liquidity worsens for buyers, but may increase for sellers, if the effect of a change in demand elasticity surpasses that of a parallel shift in demand. Perhaps surprisingly, QE might result in dealers having higher preferred inventory, as they capitalize on the buyers' higher willingness to pay if demand elasticity decreases enough.

In the search model by Duffie et al. (2005), QE can be interpreted as a decrease in three different factors: (i) the overall supply of the asset, (ii) the customer-dealer meeting frequency, and (iii) the probability that the average customer sells (since the central bank has a long holding period). These factors may lengthen the time investors wait to find a specific asset, increase dealers' power and the opportunity costs customers bear and, consequently, the bid–ask spread they pay. While a decrease in meeting frequency unequivocally increases bid–ask spreads, changes to the other two quantities have ambiguous effects on liquidity. Depending on whether the market is demand- or supply-constrained, a decrease in supply (or in the high-to-low type investor switching probability) may result in lower bid–ask spreads if it decreases the rate

[6] Duffie (1996) makes this point for off-the-run bonds: "…at least for many old issues, the supply curve for repo collateral is sufficiently large relative to the demand curve to drive specialness close to zero".

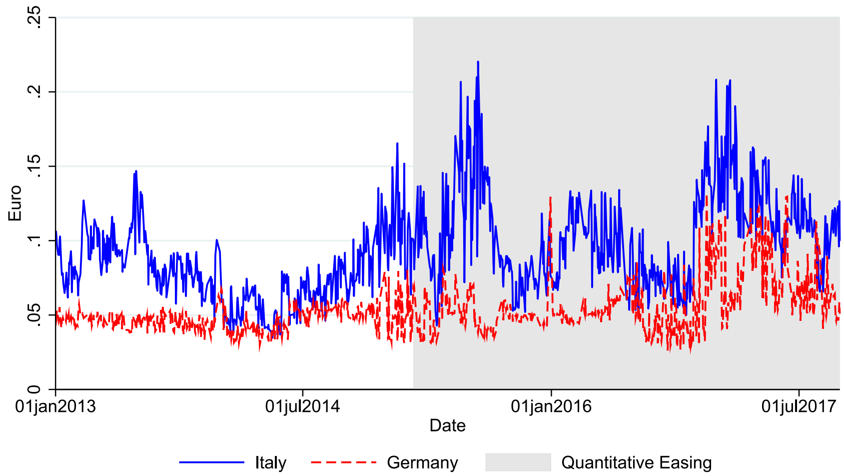

Fig. 3. Bond market illiquidity: This figure shows the time series of market illiquidity, measured by the bid–ask spread BA_{it}, for the German (in red) and Italian (in blue) CTD bonds. We compute the bid–ask spread at a one-minute frequency and average it throughout the day. The sample consists of 1057 bond-days for each of the two countries, Germany and Italy. Our sample extends from January 2013 to September 2017. The QE period when the ECB was purchasing bonds is shaded in gray and starts in March 2015. Bond price data and bond characteristics are obtained from MTS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

at which investors trade through the dealer. The impact on bid- and ask-side liquidity is similarly ambiguous. In Section IA.2 of the Internet Appendix, we elaborate further on the mechanisms at play.

In keeping with the inconclusive theoretical arguments, existing empirical literature reaches mixed results regarding whether asset purchases by the central bank reduce or increase liquidity: Schlepper et al. (2020) show that flow effects during the first year of PSPP purchases worsened market liquidity. D'Amico and King (2013), however, show that the Federal Reserve System's large-scale asset purchases improved overall liquidity. Kandrac and Schlusche (2013) find no effect while Christensen and Gillan (2022) show that QE lowers the liquidity premiums of the targeted securities.

As far as our sample is concerned, Fig. 3 shows the time-series of the bid–ask spread for the CTD bond for the German and Italian futures contracts. Noticeably, the highest levels of illiquidity were reached during the QE period for both countries. While an upward trend is visible for both time-series, the identity of the CTD bond and, with it, the characteristics of the bond that determine its liquidity, varies through time. We turn to the regression analysis to establish whether central bank purchases affected bond market liquidity.

We regress the bid–ask spread of the CTD bond for country i on day t, BA_{it}, on the fraction of bonds of that country held at the ECB, $ECB^{\%}_{it}$, and a series of control variables. We estimate

$$BA_{it} = \alpha + \beta_1 ECB^{\%}_{it} + \beta_2 DE_{it} + \beta_3 Long_{it} + \beta_4 AmtIssued_{it} + \beta_5 \sigma_{it} + \beta_6 Volume_{it} + \beta_7 YearEnd_t + \beta_8 QuarterEnd_t + \varepsilon_{it}, \tag{5}$$

where DE_i is a dummy variable that is one, for a German asset; $Long_i$ is a dummy variable, which is one if the bond was issued with 15 years to maturity; $AmtIssued_i$ is the amount issued, in billions; σ_{it} is the bond return volatility; and $Volume_{it}$ is the traded volume, in billions. We include quarter- and year-end dummies. We control for bond-specific determinants of liquidity in order to disentangle the effect of central bank purchases on market liquidity of the CTD bond's characteristics from that of the ECB holdings, following the findings in Pelizzon et al. (2016).[7]

The sample for the regressions consists of one observation for the CTD bond underlying the German and Italian futures contract, respectively, for each of the 1105 trading days in our sample period, for a total of 2209 observations. Standard errors are two-way clustered, at the bond and date level. We report the results in Table 2.

In Specification 1 of Table 2, we show that, as bond scarcity increases following the central bank purchases, a 10% increase in the stock of bond holding by the ECB increased the bid–ask spread by €1.6 cents, corresponding to a 30% increase over the before-QE level, a change that is highly significant, both economically and statistically. By increasing the bid–ask spread on the cash bond market, the ECB impeded the process of price discovery, allowing the mid-price of the CTD bond to further diverge from its futures contract counterpart before arbitrage forces could profitably intervene and enforce their convergence.

Including bond-specific determinants of market liquidity or year- and quarter-end dummies does not significantly alter our conclusions, as we show in Specification 2. As we show in Section 6, the liquidity for all Italian and German long-term coupon-bearing bonds decreased as they were purchased by the ECB during the QE period. The results are robust to including the lagged dependent variable as a regressor, as shown in Section 5.4.

To isolate the contribution to the increase in the bid–ask spread of the purchases by the central bank and rule out that other factors may have impacted the liquidity of sovereign bond markets, such as, e.g., a wider adoption of Basel III regulations, we take a difference-in-difference approach. We create a control group by calculating the daily average bid–ask spread for all short-term bills: The ECB's QE targeted only bonds with a remaining maturity of more than two years (one year from December 2016). To support the claim that the two samples are comparable, we plot the parallel trends of their liquidity measures

[7] On-the-run bonds tend to be more liquid and special than their off-the-run counterparts. However, as treasury yields are currently far below 6%, CTD bonds are the ones with the lowest duration i.e., the shortest maturities and highest coupons, which in our sample of declining yields typically correspond to off-the-run bonds. All but one CTD bond are off-the-run. In Table IA-1 of the Internet Appendix, we replicate the main analyses in the paper and include controls for a bond's time-to-maturity and on-the-run status. The results are unchanged in terms of economic and statistical significance. As only one out of the 18 CTD bonds is on-the-run, we are cautious in interpreting the parameter for the associated dummy. In our analyses, we include a dummy for bonds issued with 15 years to maturity, as this tenor is relatively uncommon and, hence, these bonds might differ from the benchmark 10-year-to-maturity bonds in some aspects, e.g. holder composition.

Table 2
Bond market illiquidity and quantitative easing: This table shows the results for the regression of the cheapest-to-deliver (CTD) bond's bid–ask spread, BA_{it}, on the fraction of bonds of that country held at the ECB, $ECB^{\%}_{it}$, for country i and day t. We control for bond-specific determinants of liquidity: the nationality of the bond by including DE_i, a dummy that is one for the German bond and zero otherwise; the volatility of the bond returns, σ_{it}; the bond's traded volume, $Volume_{it}$, in billions; whether the bond was a 15-year bond originally with the $Long_{it}$ dummy; and the amount issued in billions, $AmtIssued_{it}$. We include quarter- and year-end dummies. In Specification 3 we perform a difference-in-difference analysis, comparing the illiquidity of the CTD bond with the average illiquidity of short-term Treasury bills, which were not purchased in the context of the QE. $Bill_{it}$ is a dummy that is zero for the CTD bond, and one for the short-term Treasury bills series. Due to data quality for the German bill series, we restrict the analysis in Specification 3 to the Italian sample. We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are two-way clustered at the bond and day level. The sample is based on high-frequency quotes from 1105 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to September 2017. Bond price data and bond characteristics are obtained from MTS.

	(1) BA_{it}	(2) BA_{it}	(3) BA_{it}
$ECB^{\%}_{it}$	0.159***	0.120**	0.220**
	(3.832)	(2.661)	(2.728)
$ECB^{\%}_{it} \times Bill_{it}$			−0.198**
			(−2.442)
$Bill_{it}$			−0.021**
			(−2.875)
DE_i	−0.044***	−0.036***	
	(−9.321)	(−5.473)	
σ_{it}		0.031***	0.041***
		(5.892)	(9.704)
$Volume_{it}$		−0.100***	−0.081***
		(−6.521)	(−5.271)
$Long_{it}$		0.014**	0.011
		(2.424)	(1.708)
$AmtIssued_{it}$		0.001	
		(0.548)	
$YearEnd_t$		0.026**	0.019
		(2.117)	(1.534)
$QuarterEnd_t$		0.001	0.001
		(0.328)	(0.739)
Adj. R^2	0.462	0.598	0.869
Obs	2209	2209	2208

(and the other dependent variables used in this section) in Section IA-3 of the Internet Appendix. We restrict the analysis in Specification 3 to the Italian sample, since MTS does not have a good coverage of German Treasury bills: We observe trading for Italian short term bonds on 63% of the trading days. By contrast, German bills trade only on 4% of trading days. The results in Specification 3 of Table 2 confirm that only the bonds that were purchased by the ECB became more illiquid during the QE period. The parameter for $ECB^{\%}_{it}$ is statistically and economically significant; however, the sum of this parameter with the interaction between $ECB^{\%}_{it}$ and $Bill_{it}$, a dummy that is equal to 1 for the control sample, is not statistically different from zero.

Bid–ask spreads may represent a poor proxy for market liquidity costs if they often coincide with the market's minimum tick size and show little variation. In the European bond market, however, this is a remarkably unusual occurrence. Both in the literature (Pelizzon et al., 2016; De Roure et al., 2019; Schlepper et al., 2020) and in our sample, the average bid–ask spreads for German and Italian government bonds are much larger than the usual 1 bp tick-size, supporting the use of the bid–ask spreads as a liquidity measure. For robustness, we replicate the results in Table 2 using alternative liquidity measures: the quantity posted at the best-bid and ask, and in aggregate on the bid- and ask-sides; "deep" bid–ask spreads, or the loss a trader would incur if they contemporaneously bought and sold 2.5/5/15/30/50 million euros; the steepness of the book. Tables IA-2 and IA-3 in the Internet Appendix show that our results do not depend qualitatively on the specific definition of market liquidity considered. Table IA-4 shows that liquidity decreased similarly on the bid and ask sides of the market.

4.2. Quantitative easing and repo specialness

A second channel through which the QE affects the futures-bond basis is through the cost of borrowing the bond on the repo market. To calculate $Basis_{it}$ in Fig. 2, we use the European GC rate to capture the rate earned by an arbitageur when they borrow the bond and lend cash. In transactions that take place at the GC rate, it is not specified which particular bond in a basket the cash-lender receives.

A transaction where the cash-lender specifies which bond to borrow is a "special" repo transaction, which would take place at the special repo rate. When a particular security is scarce and hard to come by, a security-lender can borrow money at a rate lower than the GC rate, and lend that security as collateral. $Specialness_{t,t+1}$ in Eq. (4) refers to the loss of earning for an arbitrageur who lends cash at a rate lower than the GC rate.

We report in Panel A of Fig. 4 the European GC repo rate and a daily measure of special repo rates for the CTD bond. $RepoRate_{it}$ is calculated for country i, on day t, as the quantity-weighted average special repo rate from the CTD bond. We consider transactions from the MTS and BrokerTec platforms with a tomorrow-next, spot-next, or overnight term, which make up 98% of all transactions in our sample. We consider the slope of the term structure of repo rates in Section 4.3.

Panel B of Fig. 4 shows the CTD bond specialness, the difference between the European GC and $RepoRate_{it}$, $Specialness_{it} = GC_t - RepoRate_{it}$. While special repo rates were fairly close to the GC rate in the first half of the sample, $Specialness_{it}$ increased as QE made bond scarce, especially for the German market: as more and more bonds were held at the central bank, institutions looking for collateral had to obtain it on the repo market via a reverse repo transaction, and accept lower interest gains.

We test how CTD repo rates were affected by scarcity through regressing $Specialness_{it}$ on $ECB^{\%}_{it}$, the proportion of bonds held by the ECB, and other covariates. We report in Table 3 the results of estimating:

$$\begin{aligned} Specialness_{it} =& \alpha + \beta_1 ECB^{\%}_{it} + \beta_2 DE_{it} + \beta_3 \sigma_{it} + \beta_4 AmtIssued_{it} \\ &+ \beta_5 BA_{it} + \beta_6 Long_{it} \\ &+ \beta_7 YearEnd_t + \beta_8 QuarterEnd_t + \varepsilon_{it} \end{aligned} \tag{6}$$

Specification 1 shows that a 1% increase in the holding of sovereign bonds at the ECB increases their specialness by 2.77 bp, a significant increase over the pre-QE specialness of 5 bp. From the point of view of an arbitrageur, the collateral scarcity resulting from the ECB's QE increased the specialness of sovereign bonds, which decreased her gains from lending cash in exchange for borrowing the CTD bond.[8]

[8] There is a second segment of the broadly-defined securities lending market, the "sec-lending" market (Adrian et al., 2013). Both repurchase agreement and sec-lending transactions resemble collateralized loans, but differ in some legal and institutional aspects (Ruchin, 2011; Huszar and Simon, 2022; Adrian et al., 2013). We focus here on the repo market, which is the key money-market for monetary policy implementation. However, we obtain data for the sec-lending market from Markit, and confirm that all our findings hold in the

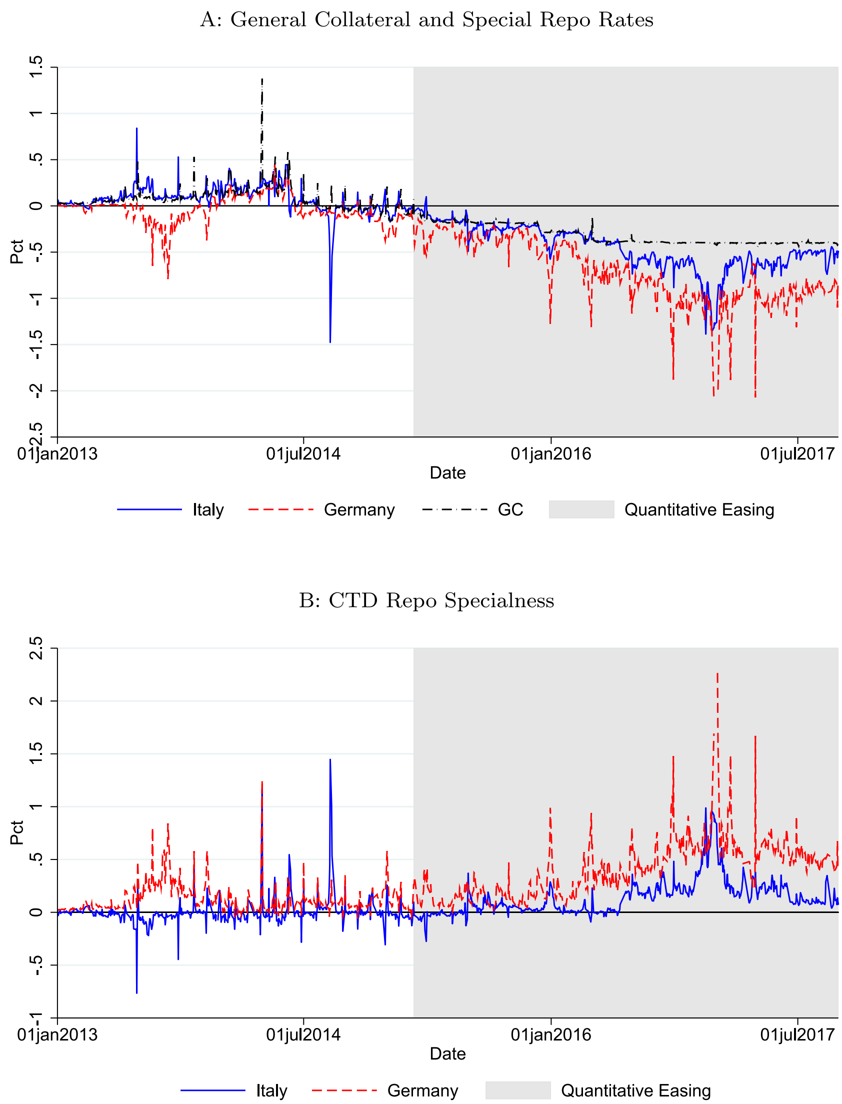

Fig. 4. General collateral, special repo rates, and specialness: This figure shows the time series of the repo rates for Germany and Italy. Panel A shows the daily special repo rates for the CTD bonds, measured as the volume-weighted average special repo rate of all transactions with a one-day term, for the German (in red) and Italian (in blue) CTD bonds. The dot-dashed black line represent European general collateral rate, GC_t, with a one-day term. Panel B plots the CTD bond specialness, $Specialness_{it}$, defined as the difference between the European GC rate and the CTD special repo rate, measured as the volume-weighted average special repo rate of all transactions with a one-day term. Repo data are obtained from the MTS group and from BrokerTec. The European GC rate is from Bloomberg. Our sample extends from January 2013 to September 2017. The QE period when the ECB was purchasing bonds is shaded in gray and starts in March 2015. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In Specifications 2, we include bond-specific characteristics on the right-hand side, which does not affect the significance of our results.[9] In fact, the result that specialness increased during the QE period can be shown to hold for all QE-eligible Italian and German bonds, as we show in Section 6.

In Specification 3, we repeat the difference-in-difference approach from Section 4.1, and compare the specialness of the treated group, the Italian and German CTD bonds, to that of the control group, the short-term bills of the corresponding country, which were not purchased by the ECB. While the long-term bonds are not more special than their short-term counterparts prior to the intervention, as $Bill_{it}$ is not statistically significant, ECB purchases increase specialness significantly more for the CTD than for the short-term bonds, with a 1% increase in overall sovereign bonds held at the ECB driving specialness up for the short-term bonds by 1.09 bp (2.69 – 1.78 = 0.9 bp), which we interpret as a spillover effect.

In a contemporaneous paper, using proprietary ECB bond purchase data, Arrata et al. (2020) reach similar conclusions using bond-specific purchases, rather than aggregate purchases, as we do. Their analysis, however, focuses on flow rather than stock effects, which explain short-term changes in the repo rate, rather than longer term, stock-driven trend dynamics, which we focus on. Corradin and Maddaloni (2020) confirm that an earlier central bank intervention affected repo specialness for Italian bonds.

broader securities lending market, i.e., both sec-lending and repo markets. Results are available upon request.

[9] The repo rates series are stationary. We verify the non-stationarity of both the series and the residuals of Specification 1 with an Augmented Dickey–Fuller test with two lags, and we cannot reject, at the 1% confidence level, the alternative hypothesis of an absence of a unit-root in the series for either country. In other words, the trends in Fig. 4 are of a deterministic kind, linear in ECB holdings, and not of a stochastic nature. We show the stationarity of the variables of interest in Section 5.4.

Table 3

Repo specialness and quantitative easing: This table shows the results for the regression of the cheapest-to-deliver (CTD) repo specialness, $Specialness_{it}$, on a measure of QE-driven scarcity. $Specialness_{it}$ is obtained at the country i and day t level, and is calculated as the difference between the European general collateral repo rate and the bonds' transaction volume-weighted special repo rate. We capture scarcity as the fraction of bonds of that country that are held at the ECB, $ECB^{\%}_{it}$. We control for bond characteristics: nationality, by including DE_i, a dummy that is one for the German contract and zero otherwise; returns volatility, σ_{it}; bid–ask spread, BA_{it}; original maturity, $Long_{it}$ is one if it was issued as a 15-year bond; and amount issued, $AmtIssued_{it}$, in billions. We include quarter- and year-end dummies. In Specification 3, we perform a difference-in-difference analysis, comparing the specialness of the CTD bond with the average specialness of short-term treasury bills, which were not purchased in the context of the QE. $Bill_{it}$ is a dummy that is zero for the CTD bond and one for the short-term Treasury bills series. We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are two-way clustered at the bond and day level. The sample is based on high-frequency quotes from 1105 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to September 2017. Bond price data and bond characteristics are obtained from MTS. Repo transactions data are provided by the MTS Group and BrokerTec.

	(1) $Specialness_{it}$	(2) $Specialness_{it}$	(3) $Specialness_{it}$
$ECB^{\%}_{it}$	2.766***	2.232***	2.689***
	(5.707)	(3.884)	(6.201)
$ECB^{\%}_{it} \times Bill_{it}$			−1.784***
			(−3.463)
$Bill_{it}$			0.046
			(1.392)
DE_i	0.145***	0.112***	0.137***
	(3.893)	(3.018)	(6.524)
σ_{it}		−0.002	0.016
		(−0.101)	(0.824)
BA_{it}		0.421	0.112
		(0.853)	(0.480)
$Long_{it}$		−0.040	
		(−0.660)	
$AmtIssued_{it}$		0.017	
		(1.479)	
$YearEnd_t$		0.641	0.260
		(1.622)	(1.671)
$QuarterEnd_t$		0.016	0.009
		(0.469)	(0.527)
Adj. R^2	0.454	0.520	0.630
Obs	2208	2208	4315

4.3. Quantitative easing and the term of the repo specialness

The rate $r_{t,T}$ in Eq. (1) represents the cost of carry, the rate for a repo transaction to borrow the CTD bond from day t to delivery T. In Eq. (4), we decompose $r_{t,T}$ into two components: The overnight specialness, i.e., the "level" of the term structure of repo rates; and a term component, the additional cost of borrowing the bond for longer than overnight.

In Section 4.2, we show that $Specialness_{it}$ increases as the ECB purchases accentuate bond scarcity; if investors expect the ECB purchases to continue, and the specialness to increase, they should demand a higher premium for lending the bond for a longer period of time than if they were to lend the bond overnight. An increase in the slope of the specialness term structure, $SpecialnessSlope_{t,T}$, would constitute a further friction to an arbitrageur trading the futures-bond basis.

Term repo transactions are rare in our sample, constraining us from characterizing bond-specific term-structures of repo rate. Hence, to test whether ECB purchases affected the slope of the term structure of the CTD repo rate, we take two approaches. The first relies on employing a relation between observable overnight repo rates dynamics and their term structure, as in Vasicek (1977). The second approach involves characterizing a common term structure, pooling all repo transactions.

To our knowledge, there is no explicit model for the term structure of repo rates. D'Amico and Pancost (2022) develop a model for bond prices that accounts for specialness but, as repo transactions last a single period, their model cannot deliver a term structure of repo rates. However, one can think of the special repo rate as a component of the bond yield, in that a decrease in the repo rate decreases the required return of the bond (Duffie, 1996).[10] Applying standard models for the interest rate process to repo rates, as in Vasicek (1977), shows that a higher volatility of the instantaneous special repo rate translates into a lower slope of the term structure of repo rates. As specialness is negatively related to the special repo rate, a higher repo rate (or specialness) volatility translates into a higher slope for the term structure of specialness. For this first approach, we calculate the dispersion of the specialness of the CTD bond, as its interquartile spread, $SpecialnessRange_{it}$, or, alternatively, its standard deviation, $SpecialnessVol_{it}$. We plot the time series of $SpecialnessRange_{it}$ in Fig. 5.

For our second approach, we aggregate all special repo transactions for each country and day into two maturity buckets: the first containing overnight transactions, and a second transactions with a term of five days or longer. We then calculate $SpecialnessSlope_{it}$ as the difference between the average specialness for the two buckets, obtaining a country-specific daily slope of the repo term structure. The assumption behind this approach is that the term structure of repo rates is homogeneous at a country-day level.

To investigate this third channel through which the QE can affect relative pricing between bonds and futures, we regress $SpecialnessRange_{it}$, $SpecialnessVol_{it}$, and $SpecialnessSlope_{it}$ on the amount of bonds held at the ECB and bond-specific variables, and report the results in Table 4:

$$SpecialnessRange_{it} = \alpha + \beta_1 ECB^{\%}_{it} + \beta_2 DE_{it} + \beta_3 \sigma_{it} + \beta_4 AmtIssued_{it} + \beta_5 BA_{it} + \beta_6 Long_{it} + \beta_7 YearEnd_t + \beta_8 QuarterEnd_t \varepsilon_{it} \quad (7)$$

Specification 1 in Table 4 shows that a 10% increase in the quantity of bonds held at the central bank increased the dispersion in the repo specialness for transactions involving the CTD bond by 4 bp, over a pre-QE average of 3 bp. Specifications 2, 3, and 4 confirm the finding even after including bond-specific controls and using the other measures. The increased dispersion and steeper term structure, resulting from the CTD bond's scarcity, hinders the price discovery process, resulting in an increased carry cost borne by the arbitrageur. In Section 6 we show that the repo dispersion increased for all long-term bonds during QE.

In Specifications 5 and 6, we repeat the difference-in-difference approach from the previous sections and compare the volatility of the specialness of the treated group, the German and Italian CTD bonds, to that of the control group, the short-term bills of the corresponding country, which were not purchased by the ECB. While the specialness of the long-term CTD bonds is less volatile than that of the short-term bonds, the scarcity following ECB purchases has a high and positive effect on the dispersion of specialness for CTD bonds and a 74%–82% smaller effect on short-term bonds, confirming our hypothesis.

The dispersion in the repo rate can affect the futures-bond basis through another channel. In the absence of term transactions, an arbitrageur shorting the bond would need to roll-over her repo position

[10] From Proposition 1 in Duffie (1996), we can derive the relationship between a bond's yield and its special repo rate. The yield of a zero-coupon bond that trades on special is $y = \frac{100}{P}\frac{1+R}{1+r} - 1$, i.e., a function of the price P of an identical bond that trades at the general collateral repo rate, of the unsecured borrowing and lending rate r, and of the special repo rate R. It is clear that yield and repo rate are positively related.

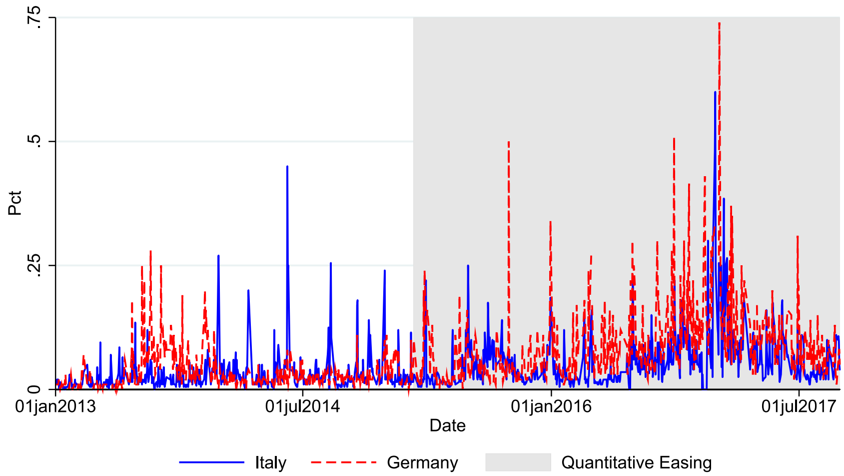

Fig. 5. Repo specialness dispersion: This figure shows the time series of the dispersion of the specialness for the CTD bonds, $SpecialnessRange_{it}$. We measure the dispersion as the difference between the 75th and the 25th percentile of the distribution of the repo specialness for transactions involving the German (in red) and Italian (in blue) CTD bonds. The specialness is calculated as the difference between the special repo rate for the CTD bond and the European general collateral rate. We consider transactions that have a one-day term. Bond and repo data are obtained from the MTS group and from BrokerTec. Our sample extends from January 2013 to September 2017. The QE period when the ECB was purchasing bonds is shaded in gray and starts in March 2015. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Specialness dispersion and quantitative easing: This table shows the results for the regression of measures of dispersion of the CTD bond's specialness on a measure of QE-driven scarcity. The dispersion is measured as $SpecialnessRange_{it}$, defined as the difference between the 75th and the 25th percentile of the distribution of the CTD bond repo specialness for the CTD Bond for country i on day t. Alternatively, we capture the dispersion as $SpecialnessVol_{it}$, the standard deviation of that same distribution. Finally, we calculate a country-specific slope of the term structure of the repo specialness, $SpecialnessSlope_{it}$, as the difference between the average specialness for trades with a term of five days or longer and the average specialness for over-night trades, for all repo trades of country i on day t. We control for bond characteristics: nationality, by including DE_i, a dummy that is one for the German contract and zero otherwise; returns volatility, σ_{it}; bid–ask spread, BA_{it}; original maturity, $Long_{it}$ is one if it was issued as a 15-year bond; and amount issued, $AmtIssued_{it}$, in billions. We include quarter- and year-end dummies. In Specifications 5 and 6, we perform a difference-in-difference by comparing $SpecialnessRange_{it}$ and $SpecialnessVol_{it}$ for the CTD bond with the corresponding average for short-term Treasury bills, which were not purchased by the ECB. $Bill_{it}$ is a dummy that is zero for the CTD bond and one for the short-term treasury bills series. We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are two-way clustered at the bond and day level, apart from Specification 4, where the left-hand side variable is measured at the country-level, where we cluster by country-delivery and date. The sample is based on high-frequency quotes from 1105 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to September 2017. Bond price data and bond characteristics are obtained from MTS. Repo transactions data are provided by the MTS Group and BrokerTec.

	(1) $Spec.Range_{it}$	(2) $Spec.Range_{it}$	(3) $Spec.Vol_{it}$	(4) $Spec.Slope_{it}$	(5) $Spec.Range_{it}$	(6) $Spec.Vol_{it}$
$ECB^{\%}_{it}$	0.423***	0.286*	0.249**	0.244**	0.516***	0.390***
	(3.847)	(1.998)	(2.439)	(2.196)	(3.323)	(3.491)
$ECB^{\%}_{it} \times Bill_{it}$					−0.456**	−0.306**
					(−2.789)	(−2.515)
$Bill_{it}$					0.026***	0.018**
					(2.888)	(2.510)
DE_i	0.010	0.008	−0.001	0.075***	0.011*	0.008*
	(1.150)	(1.034)	(−0.127)	(9.366)	(2.055)	(2.035)
σ_{it}		0.001	0.001		0.004	0.004
		(0.199)	(0.275)		(0.736)	(0.918)
BA_{it}		0.073	0.038		0.014	0.013
		(0.762)	(0.423)		(0.255)	(0.317)
$AmtIssued_{it}$		0.004	0.002			
		(1.595)	(1.514)			
$Long_{it}$		0.002	−0.007			
		(0.139)	(−0.830)			
$YearEnd_t$		0.070***	0.061***	−0.055***	0.103	0.080
		(2.969)	(5.609)	(−2.794)	(1.388)	(1.417)
$QuarterEnd_t$		0.025**	0.019***	−0.001	0.019***	0.016***
		(2.662)	(3.242)	(−0.111)	(3.449)	(3.864)
Adj. R^2	0.255	0.317	0.372	0.258	0.216	0.242
Obs	2208	2208	2204	1806	4315	4309

Table 5
Frictions, Arbitrage, and residual effect of quantitative easing: This table shows the results for the regression of measures of interest rate market functioning on a measure of QE-driven scarcity. The dependent variables are: $Basis_{it}$, the difference in pricing between sovereign futures contracts and underlying bonds, for country-i on day-t, where a positive basis implies that bonds prices are higher than those for futures contracts; the daily, 1-min return correlation between a futures contract and an equally weighted portfolio of deliverable bonds, $Corr_{it}$; $ImpliedRepo_{it}$, the repo rate a bond would need to trade at for the basis to be zero; $TradeBasis_{it}$, that is $Basis_{it}$ net of trading and security-borrowing costs. The main explanatory variable is $ECB^{\%}_{it}$, the fraction of bonds held at the ECB. We control for the nationality of the contract, with the dummy variable DE_i, and deterministic year-end and quarter-end effects. We control for frictions to the arbitrage process, that is the CTD bond's bid–ask spread, BA_{it} and specialness, $Specialness_{it}$. We proxy for the cost of carry using the slope of the repo specialness term structure, $SpecialnessSlope_{it}$, calculated as the difference between the average specialness for trades with a term of five days or longer and the average specialness for over-night trades, for all repo transactions of country i on day t, and $SpecialnessRange_{it}$, the difference between the 75th and the 25th percentile of CTD bond repo specialness. We capture the quality option embedded in the futures contract with the volatility of the return differential between first and second CTD bond, $\sigma 12_{it}$, and their price ratio, $P12_{it}$. *, **, and *** indicate that parameters are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are clustered at the delivery-country and date level. The sample extends from January 2013 to September 2017, resulting in 1105 observations each for the two countries we consider, Germany and Italy. Bond (futures) data are from MTS (Eurex). Data on the European general collateral rates are from Bloomberg.

	(1) $Basis_{it}$	(2) $Corr_{it}$	(3) $ImpliedRepo_{it}$	(4) $Basis_{it}$	(5) $Corr_{it}$	(6) $ImpliedRepo_{it}$	(7) $TradeBasis_{it}$	(8) $TradeBasis_{it}$
$ECB^{\%}_{it}$				0.025***	−0.203***	−3.141***	0.012**	0.011*
				(2.941)	(−4.217)	(−4.264)	(2.361)	(1.773)
DE_i	0.003***	0.070***	−0.305***	0.002***	0.074***	−0.265***	0.002***	0.002***
	(3.467)	(6.650)	(−3.768)	(3.639)	(7.406)	(−4.548)	(3.949)	(3.518)
BA_{it}	0.032***	−0.109	−3.583***	0.019**	−0.012	−1.895***		
	(3.305)	(−0.948)	(−4.321)	(2.075)	(−0.111)	(−2.795)		
$Specialness_{it}$	0.007***	−0.026**	−0.715***	0.005**	−0.003	−0.364**		
	(2.882)	(−2.147)	(−3.033)	(2.243)	(−0.838)	(−2.615)		
$Spec.Range_{it}$	0.017**	−0.060	−1.740**	0.013***	−0.029	−1.234***		0.012***
	(2.359)	(−1.456)	(−2.515)	(2.896)	(−0.967)	(−3.406)		(2.990)
$Spec.Slope_{it}$								0.005***
								(3.169)
$YearEnd_t$	−0.004***	0.010	0.363***	−0.001	−0.009	0.052	−0.005	−0.002*
	(−3.606)	(0.850)	(4.474)	(−0.851)	(−0.903)	(0.481)	(−1.566)	(−1.898)
$QuarterEnd_t$	−0.001	0.005	0.071*	0.000	0.005	0.055	0.001	0.001*
	(−1.234)	(1.421)	(1.738)	(−0.936)	(1.391)	(1.604)	(1.684)	(1.840)
$\sigma 12_{it}$				0.000		−0.069	−0.002	−0.002
				(0.297)		(−0.818)	(−1.539)	(−1.639)
$P12_{it}$				−0.005		0.609	−0.004	0.001
				(−0.286)		(0.405)	(−0.237)	(0.054)
Adj. R^2	0.607	0.541	0.639	0.668	0.576	0.741	0.195	0.266
Obs	2208	2194	2208	2165	2194	2165	2165	1776

daily, exposing herself to the repo rollover risk. We elaborate on this point in the next section.

5. Arbitrage opportunities, securities lending facility, and regulatory frictions

Section 3 documents that $Basis_{it}$ increases in the fraction of bonds held at the ECB. We next show that the effect occurs through the channels we consider in Section 4 and quantify the contribution of each friction. Consistent with the decomposition in Eq. (4), we extend the regression in Eq. (3) to include BA_{it}, $Specialness_{it}$, and $SpecialnessRange_{it}$:

$$
\begin{aligned}
Basis_{it} = \alpha + \beta_1 ECB^{\%}_{it} + \beta_2 DE_{it} + \beta_3 BA_{it} + \beta_4 Specialness_{it} \\
+ \beta_5 SpecialnessSlope_{it} \\
+ \beta_6 QuarterEnd_t + \beta_7 YearEnd_t + \varepsilon_{it} \qquad (8)
\end{aligned}
$$

We report the results in Table 5. Specification 1 and 2 show that the three channels we consider contribute to the worsening of the pricing efficiency in the market for interest rates: As bonds become scarcer and their market and funding liquidity deteriorates, the relative pricing (correlation) between bonds and futures widens (decreases).

The three frictions are significant at the 1% level and explain 61% (54%) of the variation in $Basis_{it}$ ($Corr_{it}$).[11] Funding and carry cost have the largest economic impact: A one-standard deviation increase in BA_{it} increases $Basis_{it}$ by 0.24 standard deviations. A similar increase in $Specialness_{it}$ and $SpecialnessRange_{it}$ increases $Basis_{it}$ by 0.49 and 0.21 standard deviations, respectively, indicating that frictions faced in the repo market were the largest determinant of the disconnect between the cash bond and futures markets.[12] Results for $Corr_{it}$ are similar, since a one-standard deviation increase in $Specialness_{it}$ reduces the hedging effectiveness of using a futures contract by 0.16 standard deviations, about twice the magnitude of a similar increase in the other two frictions.

We introduce an alternative for measuring the difference in relative pricing between bonds and futures, which is to calculate the derivative-implied risk-free rate, or implied repo rate, $ImpliedRepo_{it} = \left(\frac{F_t \cdot CF + A_T}{B_t + A_{i,t+2}} - 1\right)\frac{360}{T-(t+2)}$, from which we subtract the ECB's deposit facility rate to adjust for four discrete jumps in the series. This measure is common in the works that focus on the difference between derivative-implied risk-free rates (Fleckenstein and Longstaff, 2020; Hazelkorn et al., 2022; Van Binsbergen et al., 2022). We report the series in Figure IA-9. In Specification 3, we repeat Specification 2 with $ImpliedRepo_{it}$ as dependent variable and, consistent with our previous analyses, we find that a one-standard deviation in $Specialness_{it}$ decreases the implied

[11] Standard errors are clustered at the delivery-country- and date-level. Results based on Driscoll and Kraay (1998) (unreported) deliver higher t-values.

[12] When $Corr_{it}$ is the dependant variable, we employ costs variables based on the CTD alone, for simplicity. Results based on costs for all deliverable bonds, reported in Table IA-5 of the Internet Appendix, are virtually identical.

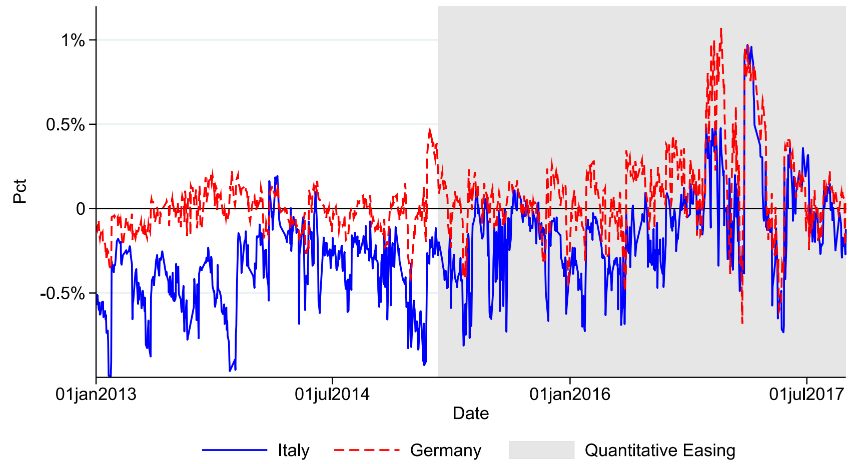

Fig. 6. Futures-bond arbitrage opportunities: This figure shows the time series of arbitrage profit a trader would have made if she were to sell the bond and buy the corresponding futures contract for Germany (in red) and Italy (in blue), $TradeBasis_t$. The tradable basis is calculated at a one-minute frequency according to Eq. (9) and averaged across the day, and is calculated as an annualized return. We assume the arbitrageur establishes the position by selling the bond at the bid price, and buying the futures at the ask price, and that the repo transaction needed to establish the bond position took place at the transaction volume-weighted average special repo rate for that day. Bond data are obtained from the MTS group, and futures data are obtained from Thomson Reuters for the Eurex market. The repo rate is from transactions that took place on the MTS Repo and BrokerTec platforms. Our sample extends from January 2013 to September 2017. The QE period when the ECB was purchasing bonds is shaded in gray and starts in March 2015. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

repo by twice as much (0.47 standard deviations) as a similar change to the other frictions.

As we find that scarcity increases the treasuries' convenience yield, our results differ from those by Van Binsbergen et al. (2022), who focus the Federal Reserve's QE efforts. While interesting, studying this difference is beyond the scope of this paper, and may relate to more significant asset scarcity in the Eurozone (Schaffner et al., 2019), the term of the rate we consider (long- vis-à-vis short-term rates), or safety vs. liquidity scarcity (Vissing-Jorgensen, 2019).[13]

To gauge whether the QE-driven scarcity had residual effects on the basis, we repeat the analysis and include $ECB^{\%}_{it}$ as a regressor. We report the results in Specifications 4–6 of Table 5. We also calculate the profit an arbitrageur would earn if they engaged in the bond-futures trade, netting $Basis_{it}$ in Eq. (1) from costs, by replacing the bond price with its bid-quote, B^{Bid}_t, futures price with its ask-quote, and GC rate with the special repo rate $RepoRate_{it}$, and obtaining:

$$TradeBasis_{it} = \left[\left(B^{Bid}_t + A_{i,t+2} \right) \left(1 + \frac{T-(t+2)}{360} R_{t,t+1} \right) - A_T - F^{Ask}_t \cdot CF \right] \left(\frac{T-t}{365} \right)^{-1}. \quad (9)$$

$TradeBasis_{it}$, shown in Fig. 6, is obviously lower than $Basis_{it}$ and often significantly negative. An arbitrageur would not engage in the trade on such days. Overwhelmingly, however, $TradeBasis_{it}$ is positive during, and not prior, QE: 72% of days when $TradeBasis_{it}$ is positive happen during QE. We repeat the analysis using $TradeBasis_{it}$ as dependent variable and reports the results in Specification 7 of Table 5. All specifications indicate that ECB purchases had residual effects on the relative price of futures and bonds, i.e., beyond their effects on the frictions we considered.

Residual effects can arise for two reasons. First, they can capture a temporary increase in bond prices from the sheer buying pressure of the ECB's purchases. Second, they may capture the roll-over risk premium included in the trade, which is affected by scarcity: As special term-repos are seldom available, market participants may have to rely on rolling over overnight repo positions, which leaves them exposed to increases in bond specialness and scarcity over the life of the trade. Market participants holding a synthetic short bond position need to be compensated for the risk they are taking, a component of the bond price that D'Amico and Pancost (2022) refer to as the special collateral risk premium. Specification 8 shows that $SpecialnessRange_{it}$, which proxies for roll-over risk, and $SpecialnessSlope_{it}$, capturing some degree of term-repo slope, are indeed significant at the 1% level in explaining $TradeBasis_{it}$. $ECB^{\%}_{it}$ is similarly significant in Specifications 4–8, consistent with $SpecialnessSlope_{it}$ not fully reflecting the CTD's specialness slope, if the latter is more sensitive to scarcity than the slope for the average bond, and with $SpecialnessRange_{it}$ not fully capturing the rollover–risk premium, if the latter increases in scarcity.

Our results so far support the hypothesis that the price discovery process was significantly perturbed during QE. In the remainder of this section, we argue for a causal link and rule out alternative explanations. To identify scarcity as the main driver of our results, we use an exogenous policy change in Section 5.1. Violations of the law of one price like those we observe have been linked in the literature to intermediaries' constraints. In Section 5.2, we argue that the reduction in price discovery that we observe was not primarily driven by balance sheet costs. In Section 5.3, we show that counterfactual arbitrage relations did not worsen in our sample period, as they do not involve assets that experienced significant scarcity. In Section 5.4, we conduct robustness analyses.

5.1. The cash-collateralized securities lending facility

To identify scarcity as the channel through which QE affects the efficiency of the market for interest rates, we rely on a natural experiment involving the ECB's implementation of the CCSLF, which made bonds purchased by the central bank available to be borrowed back by market participants via repo transactions, i.e., using cash as collateral.

Between April 2015 and December 2016, market participants could only borrow from central banks the securities that had been purchased under QE via repo–reverse-repo matched transactions. In other words, they could borrow a sovereign bond by pledging another safe asset as collateral (asset-collateralized security borrowing). Given that the quality of pledged asset could not be lower than the quality of the borrowed asset, these transactions did not affect the overall availability of treasuries. With the implementation of the CCSLF in December 2016, however, the ECB allowed market participants to also borrow government bonds against cash (cash-collateralized security borrowing).

[13] Paret and Weber (2019) show that the Bund scarcity led to an increase in convenience yields.

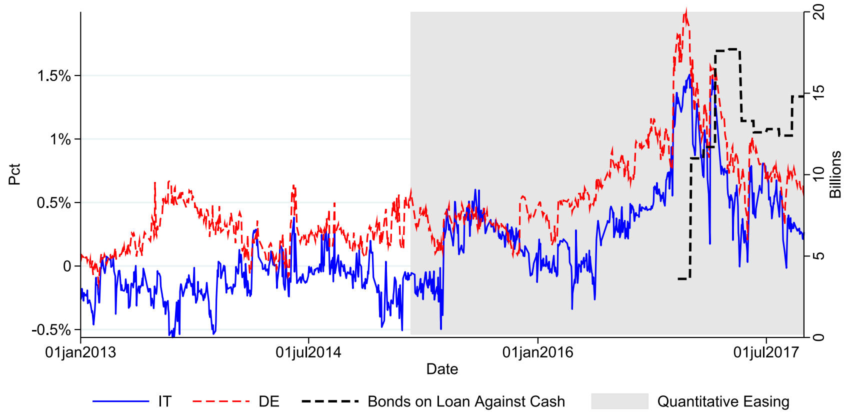

Fig. 7. $Basis_{it}$ and securities lending: This figure shows the time series $Basis_{it}$, the annualized return from buying a futures and shorting the CTD bond, in the absence of trading and funding costs. The dashed line represents the amount of bonds borrowed from the ECB against cash-collateral (on the right axes). The cash-collateralized securities lending facility was implemented in December 2016. Data on bond lending are obtained from the ECB. Data on bond prices and characteristics are obtained from MTS, data on repo transactions are obtained from MTS and BrokerTec, and futures data are obtained for the Eurex market via Thomson Reuters.

For the purpose of our identification strategy, the key difference between the two facilities is that the security-collateralized lending facility could only alleviate the scarcity differential between two bonds, and had no effect on the overall stock of safe asset available. The CCSLF, on the other hand, allowed market participants to increase the amount of treasuries available on the market, as the bonds left the ECB's holdings and entered the private market. As scarcity includes both a security-specific and a common component, the implementation of the CCSLF acted as a shock to the latter.

This policy change eased market functioning. The effect of a decrease in scarcity on the price discovery process is shown in Fig. 7, where we plot the amount of assets borrowed against cash in the Eurosystem, together with our measure of bond market efficiency, $Basis_{it}$. As QE induced scarcity, as shown in the previous sections, market functioning was impaired. Following the implementation of the CCSLF, market participants borrowed securities against cash, which increased asset availability, reduced treasury scarcity, and eased funding frictions, in turn allowing the price of the cash bond to converge to that of the futures. Accordingly, Fig. 7 shows that, following the higher CCSLF utilization in January and March, $Basis_{it}$ subsided from its highest levels.

It is worth noting that borrowing securities via the CCSLF does not affect a bank's capital ratios. The value of the leverage ratio denominator is unchanged after engaging in CCSLF, despite the increase in a bank's securities financing transactions, as the total exposure is unaffected. Similarly, the liquidity buffer in the numerator of the liquidity coverage ratio is unchanged, even if the bank's reserves decrease, as the holdings of safe assets increase by an identical amount. While their capital ratios were unchanged, market participants' ability to borrow securities from the ECB's holdings affects asset scarcity, as the cash lender obtains the right of use of the collateral and may repledge it. Internet Appendix Section IA.4 illustrates these arguments using a simple balance sheet example.

To size the impact that the CCSLF had on the market for security borrowing, we calculate the daily volume for special repo transactions that occurred on the MTS and BrokerTec platforms for all Euro-zone countries. We show the series in Figure IA-10 of the Internet Appendix. On December 14, 2016, the day before the CCSLF was implemented, the total daily special repo volume was €187 bn, with Germany and Italy accounting for 38% and 40% of the total, or 78% combined. The pricing of the CCSLF made it a viable option only for borrowing bonds that had a specialness higher than 30 bps. Of the €187 bn worth of transactions, €57 bn took place above that level, 85% of which involved German and Italian bonds. The CCSLF, thus, represented a sizeable alternative to the repo market: The average daily utilization of the CCSLF was €13 billions, a provision of security lending equal to 23% of the target market.

We show that the CCSLF implementation improved market functioning by repeating the analyses from Tables 1 and 5 and interacting $ECB^{\%}_{it}$ with $CCSLF_t$, a dummy that is one, if t follows the implementation of the CCSLF, and zero otherwise. We report these results in Table 6. For all measures of market functioning, the coefficient for the interaction term $CCSLF_t \times ECB^{\%}_{it}$ has the opposite sign to that for $ECB^{\%}_{it}$, and is significant at the 5% or 1% level. For a given level of bond holdings by the central bank, scarcity is lower if market participants can ease it by borrowing bonds against cash: lower scarcity results in an improved arbitrage mechanism, hedging ability, and market efficiency.

The coefficients for $ECB^{\%}_{it}$ are nearly double their counterparts in Table 5 in both magnitude and statistical significance, suggesting that we underestimated the effect of scarcity when we analyzed jointly the pre- and post-CCSLF periods. The sum of the parameter for ECB_{it} and its interaction with the CCSLF dummy is different from zero at the 1% level only for Specification 5, indicating that the QE purchases contributed negatively to the price discovery process only prior to the implementation of the CCSLF.

Consistently with the hypothesis that the implementation of the SFL affected scarcity, we show in Table IA-6 of the Internet Appendix that CCSLF improved market functioning by reducing the level and volatility of repo specialness, easing arbitrageurs' funding and carry costs.

5.2. Balance sheet costs

A recent strand of the literature shows that balance sheet costs—debt-overhang and bank regulatory requirements—imply a positive benchmark return for arbitrage trades (e.g., Boyarchenko et al., 2018; Du et al., 2018; Duffie, 2017; Andersen et al., 2019; Anderson et al., 2021; Klingler and Sundaresan, 2023; Rime et al., 2021). In this section, we show that accounting for the effect of balance sheet costs does not diminish the role of scarcity in explaining the impediment to the price discovery process.

Andersen et al. (2019) show that financial markets are not immune to debt overhang considerations (Myers, 1977), whereby a company (dealer) foregoes a positive-return project (trade) if the resulting profits accrue primarily to debt- rather than equity-holders. They also show that debt overhang increases a dealer's required return on a balance-sheet expanding trade proportionally to the dealer's unsecured credit spread. Funding-value adjustments aimed at reducing debt-overhang by aligning the incentives between equity-holders and traders can, thus, contribute to impeding the price discovery process.

Table 6
Scarcity and the securities lending facility: This table shows the results for the regression of measures of interest rate market functioning on a measure of QE-driven scarcity, interacted with an exogenous policy shock. The dependent variables are $Basis_{it}$, the difference in pricing between sovereign futures contracts and underlying bonds, $Corr_{it}$, the daily, 1-min return correlation between a futures contract and an equally weighted portfolio of deliverable bonds, and $TradeBasis_{it}$, that is $Basis_{it}$ net of trading and security-borrowing costs. The main explanatory variable is $ECB^{\%}_{it}$, the fraction of bonds held at the ECB, interacted with $CCSLF_t$, a dummy that is one after the ECB implemented a cash-collateralized securities lending facility, and zero otherwise. We control for the nationality of the contract, with the dummy variable DE_i, and deterministic year-end and quarter-end effects. We control for frictions to the arbitrage process, that is the CTD bond's bid–ask spread, BA_{it} and specialness, $Specialness_{it}$. We proxy for the cost of carry using the slope of the repo specialness term structure, $SpecialnessSlope_{it}$, calculated as the difference between the average specialness for trades with a term of five days or longer and the average specialness for over-night trades, for all repo transactions of country i on day t, and $SpecialnessRange_{it}$, the difference between the 75th and the 25th percentile of CTD bond repo specialness. We capture the quality option embedded in the futures contract with the volatility of the return differential between first and second CTD bond $\sigma 12_{it}$ and their price ratio $P12_{it}$. *, **, and *** indicate that parameters are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are clustered at the delivery-country and date level. The sample extends from January 2013 to September 2017, resulting in 1105 observations each for the two countries we consider, Germany and Italy. Bond (futures) data are from MTS (Eurex). Data on the European general collateral rates are from Bloomberg.

	(1) $Basis_{it}$	(2) $Corr_{it}$	(3) $Basis_{it}$	(4) $Corr_{it}$	(5) $TradeBasis_{it}$
$ECB^{\%}_{it}$	0.060***	−0.382***	0.044***	−0.371***	0.027***
	(7.987)	(−2.991)	(6.047)	(−3.007)	(3.680)
$CCSLF_t \times ECB^{\%}_{it}$	−0.088***	0.327**	−0.078***	0.314**	−0.057***
	(−4.284)	(2.688)	(−5.577)	(2.432)	(−5.630)
$CCSLF_t$	0.011***	−0.021	0.010***	−0.018	0.006***
	(3.217)	(−1.552)	(3.883)	(−1.218)	(4.922)
DE_i	0.003***	0.073***	0.003***	0.071***	0.003***
	(5.194)	(10.331)	(4.896)	(8.242)	(5.088)
BA_{it}			0.015**	−0.046	
			(2.145)	(−0.506)	
$Specialness_{it}$			0.004**	−0.003	
			(2.645)	(−0.619)	
$Spec.Range_{it}$			0.009*	0.002	0.008**
			(2.020)	(0.098)	(2.345)
$Spec.Slope_{it}$					0.005***
					(3.565)
$YearEnd_t$	0.002	−0.013	−0.001	−0.011	−0.002**
	(1.112)	(−1.444)	(−1.251)	(−1.002)	(−2.651)
$QuarterEnd_t$	0.000	0.003	0.000	0.003	0.001**
	(0.229)	(0.970)	(−0.693)	(0.983)	(2.358)
$\sigma 12_{it}$			0.001		−0.002
			(0.963)		(−1.544)
$P12_{it}$			0.017		0.019
			(1.244)		(1.308)
Adj. R^2	0.646	0.595	0.727	0.596	0.303
Obs	2209	2195	2165	2194	1776

To verify whether the debt overhang channel is at play, we replicate Specification 3 of Table 6 and include as regressors two economy-wide rates, the 3-month Euribor rate and the 10-year Germany yield, to capture changes in the short- and long-end of the risk-free rate curve, and two measures of corporate credit spread, the 5-year iTraxx Europe Senior Financials CDS index (Duffie, 2017) and the 5-year yield of an average European AAA Covered Bond. As shown in Specification 1 of Table 7, we find little support that the debt overhang channel played a significant role in the event of the market inefficiency we study.[14]

An alternative source of increasing returns on balance-sheet expanding trades, separate and incremental to the effect of debt-overhang, is capital regulation. As Duffie (2017) points out and as we detail in

[14] We include rates and spread variables in changes, as they are non-stationary. As we show in Section 5.4, the dependent variables are stationary and our analyses are robust to alternative dynamics specifications.

Table 7
Robustness: Balance sheet costs: This table shows the results for the regression of measures of interest rate market functioning on a measure of QE-driven scarcity. The dependent variable is $Basis_{it}$, the difference in pricing between sovereign futures contracts and underlying bonds, for country-i on day-t. The main explanatory variable is $ECB^{\%}_{it}$, the fraction of bonds held at the ECB, interacted with $CCSLF_t$, a dummy that is one after the ECB implemented a cash-collateralized securities lending facility, and zero otherwise. We test alternative drivers of the basis measures: the 3-month Euribor rate, $EuriborRate_t$; the interpolated 10-year yield for a generic German Bund, $10YearRate_t$; the 5-year node of the iTraxx Europe Senior Financials CDS index, $IGFinSpread_t$; the 5-year spread of the AAA Covered Bond yield curve over the German treasury, $AAACorpSpread_t$; the median leverage ratio (LR) for European globally systemically important banks, $RegRatio_t$; the term-of-the-year premium based on Euribor futures, $ToTYP_t$. Similarly to Table 6, we also control for: the nationality of the contract, with the dummy variable DE_i; the CTD bond's bid–ask spread, BA_{it}; its specialness, $Specialness_{it}$; the difference between the 75th and the 25th percentile of CTD bond repo specialness, $SpecialnessRange_{it}$. Finally, we include deterministic year-end and quarter-end effects and, to control for the quality option, the volatility of the return differential between first and second CTD bond, $\sigma 12_{it}$; and their price ratio $P12_{it}$. *, **, and *** indicate that parameters are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are clustered at the delivery-country and date level. The sample extends from January 2013 to September 2017, resulting in 1105 observations each for the two countries we consider, Germany and Italy. Bond (futures) data are from MTS (Eurex). Data on the European general collateral rates are from Bloomberg.

	(1) $Basis_{it}$	(2) $Basis_{it}$	(3) $Basis_{it}$
$ECB^{\%}_{it}$	0.043***	0.038***	0.040***
	(5.890)	(4.781)	(5.108)
$CCSLF_t \times ECB^{\%}_{it}$	−0.077***	−0.075***	−0.074***
	(−5.648)	(−5.397)	(−5.478)
$CCSLF_t$	0.009***	0.009***	0.010***
	(3.904)	(3.861)	(4.068)
DE_i	0.003***	0.003***	0.003***
	(4.715)	(4.930)	(4.971)
BA_{it}	0.014**	0.014**	0.014**
	(2.085)	(2.171)	(2.229)
$Specialness_{it}$	0.005**	0.005**	0.005**
	(2.659)	(2.625)	(2.588)
$Spec.Range_{it}$	0.008*	0.008*	0.008**
	(1.870)	(1.902)	(2.026)
$YearEnd_t$	−0.001	−0.001	−0.001
	(−0.531)	(−1.373)	(−1.262)
$QuarterEnd_t$	0.000	0.000	0.000
	(−0.702)	(−0.575)	(−0.715)
$\sigma 12_{it}$	0.001	0.001	0.001
	(1.024)	(1.316)	(1.187)
$P12_{it}$	0.018	0.028*	0.025
	(1.230)	(1.918)	(1.646)
$\Delta EuriborRate_t$	0.019		
	(0.914)		
$\Delta 10YearRate_t$	−0.001		
	(−0.700)		
$\Delta IGFinSpread_t$	−0.246*		
	(−1.695)		
$\Delta AAACorpSpread_t$	0.005		
	(1.202)		
$RegRatio_t$		0.001**	
		(2.023)	
$ToTYP_t$			−0.158
			(−1.602)
Adj. R^2	0.723	0.732	0.730
Obs	2115	2165	2165

Section IA.5 of the Internet Appendix, the Basel III–mandated ratio most likely to affect the basis is the non-risk-based leverage ratio (LR), which is obtained by dividing a bank's Tier 1 capital by the sum of its on-balance sheet exposures, derivative exposures, securities finance transaction exposures, and off-balance sheet items (BIS, 2014), $LR = \frac{\text{Tier 1 Capital}}{\text{Exposure}}$.

The LR affects participants' ability to both intermediate and engage in a cash-futures basis trade only because of the effect of repo transactions: A futures transaction increases the bank's exposure by the sum of the "current exposure", or replacement value of the position, and the "potential future exposure" (Haynes and McPhail, 2021; Boyarchenko et al., 2018) and both exposures are zero for short-term, cleared, interest rate derivatives.[15] Repo transactions, instead, affect the denominator of the LR, by increasing a bank's "securities financing transaction exposure" by the full notional amount of the trade, while reverse repos—whereby the bank borrows the security—do not.[16] If a bank intermediates a futures-bond basis trade for a client, it engages in both repo and reverse repo, increasing its exposure by the notional amount of the repo. If a trader (bank or otherwise) engages in this trade, it borrows a bond via reverse repo, which constitutes a repo for its bank counterpart.

In Figure IA-11 of the Internet Appendix, we plot the median LR for a set of European global systemically important banks. As banks gradually increased compliance with Basel III, they began to hold more capital against their exposure, and LR increased from 3% in 2013 to 5% in 2016. Similarly to our results on balance sheet costs, the LR series highlights that Basel III regulation alone cannot explain the price discovery process dynamics we document, given that the banks' leverage is nearly constant between 2016 and 2017, yet we observe significant variation in the price discovery process, a worsening throughout 2016, followed by an improvement when the CCSLF was implemented. We include the median LR as a measure of capital constraints in Specification 2 of Table 7 and, while significant, the inclusion of regulatory costs does not diminish the role of scarcity.

Finally, to rule out the possibility that the dynamics we observe for the futures-bond basis are driven by time-varying balance sheet costs that we may not fully capture with the proxies in Table 7, we calculate the turn-of-the-year premium in Euribor rates. This measure, developed by Fleckenstein and Longstaff (2020) for the US market, captures intermediary balance sheet usage. Futures contracts on Euribor rates with December expirations should price that the underlying Euribor loan is to remain on the balance sheet at year-end, while loans underlying the neighboring contracts with March and September expirations would not. Financing rates tend to spike near the end of the year, as financial institutions face additional balance-sheet-related pressures. The expected size of the year-end spike in Euribor reflected in futures contracts constitutes a measure of the intermediaries' balance sheet costs faced by institutions.

Following Fleckenstein and Longstaff (2020), we calculate the measure as the average difference between the implied Euribor rate for the December-deliveries and the neighboring March- and September-deliveries. We show the measures in Fig. 8.[17] This market-based measure indicates that balance-sheet costs did not increase during QE, but in fact decreased slightly. We include the turn-of-the-year premium as regressor in Specification 3 of Table 7 and find that it is not significant. The evidence in this section suggests that trading and funding costs generated by market participants' demand for intermediaries balance-sheet space cannot explain the disconnect we observe between cash bond and derivatives markets.

5.3. Counterfactual evidence: Put-call parity for options on futures

To further support our hypothesis that QE-driven scarcity is the main driver behind the reduction in price discovery, we consider the counterfactual of the put–call parity relation between treasury bond futures and the put and call options written on the futures contracts: Since none of the legs of this trade involves scarce cash assets, but only derivative securities, we expect to find no incremental deviation in the put–call parity during the QE period.

We calculate deviations from put–call parity as

$$PutCallParity_{k,t,T} = \Big(\underbrace{\hat{F}(t,T)}_{\text{Option-Implied Futures Price}} - \underbrace{F(t,T)}_{\text{Traded Futures Price}} \Big) \cdot e^{-r_t \cdot (T-t)}, \tag{10}$$

the discounted difference between the option-implied futures price $\hat{F}(t,T) = e^{r_t \cdot (T-t)} (c(k,t,T) - p(k,t,T)) + k$ and the corresponding traded price, $F(t,T)$, where $c(k,t,T)$ ($p(k,t,T)$) is the price at time t of a call (put) option with expiry date T and strike price k written on a futures contract with delivery date T and price $F(t,T)$. r_t is the risk-free rate. A positive $PutCallParity_{k,t,T}$ means that the synthetic futures contract is more expensive that its traded counterpart.

We obtain transaction data for options on treasury futures from Eurex. Our calculations include only options on the German futures, since options on the Italian futures contract were launched only in October 2017. We match put- and call-option transactions if they share both delivery date and strike price and they take place in the same trading minute. We restrict our analysis to options that expire on the same day as the next futures contract's delivery date and that are near the money, i.e., with a strike price up to €1.5 from the at-the-money option. Using the contemporaneous futures price, we calculate $PutCallParity_{k,t,T}$ for a €100 notional amount, scale it by time-to-exercise (or, equivalently, time-to-delivery) and aggregate it into a daily series. We use the Eonia rate as the risk-free rate.

We report the series in Fig. 9. The series is narrowly centered around zero, and does not share the dynamics of $Basis_{it}$, also reported in the figure. Consistent with our expectations, we find that the price discovery process between assets in the put–call parity trade was not affected by QE purchases. Since options and futures were not made scarce by the QE purchases, this finding is consistent with scarcity being the channel through which QE affected the price discovery process in the market for European interest rates.

5.4. Robustness

In this section, we show that our results are robust to alternative empirical specifications. First, we demonstrate that endogeneity between

[15] For cleared, marked-to-market derivatives, the current exposure is zero. The potential future exposure is calculated as $PFE = (0.4 + 0.6 \cdot NGR) \cdot A_{Gross}$, where A_{Gross} is the notional amount of the derivative position multiplied by a conversion factor that varies according to the nature of its underlying asset (BIS, 2014). The conversion factor for interest rate derivatives with a remaining maturity of less than a year is 0%; hence, both the current exposure and the potential future exposure (PFE) are zero, due to the short maturity of the futures contract we consider. For the sake of simplicity, we ignore the secondary effects of funding costs and leverage consequences of haircuts in the repo transactions and initial margins for the futures contracts.

[16] The asymmetry in the treatment of repo transactions follows from accounting standards. The cash borrower's leverage increases, in line with their liabilities. The cash-lender's total assets do not change, even though the compositions shifts in favor of securities, and neither does their liability, as the security provided as collateral remain in the balance sheet of the cash borrower, who will eventually re-obtain control (see https://www.icmagroup.org/market-practice-and-regulatory-policy/repo-and-collateral-markets/icma-ercc-publications/frequently-asked-questions-on-repo/37-is-repo-used-to-remove-assets-from-the-balance-sheet/).

[17] Figure IA-12 shows the time-series of the measure from 1999, when Euribor futures were introduced.

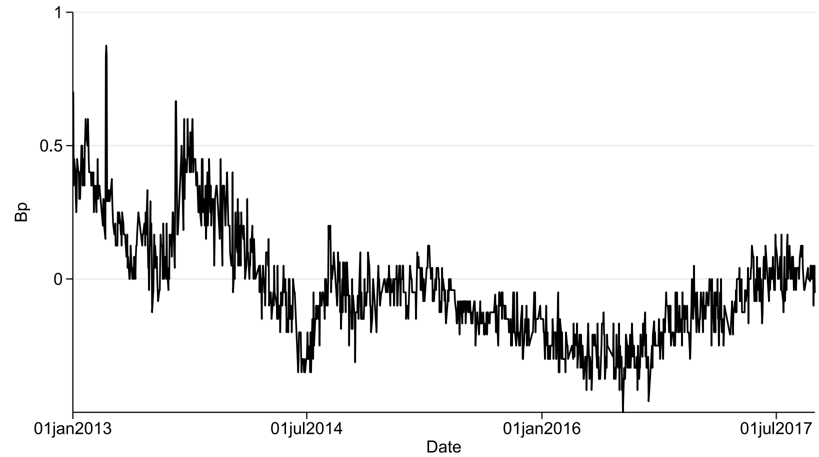

Fig. 8. Turn-of-the-Year premium: This figure shows the time series of the turn-of-the-year premium. The premium is calculated as the average difference between the Euribor rates implied from December-deliveries futures and the average rate implied by the neighboring September- and March-delivery contracts. Euribor futures data are obtained from Bloomberg. Our data cover the January 2013–September 2017 period.

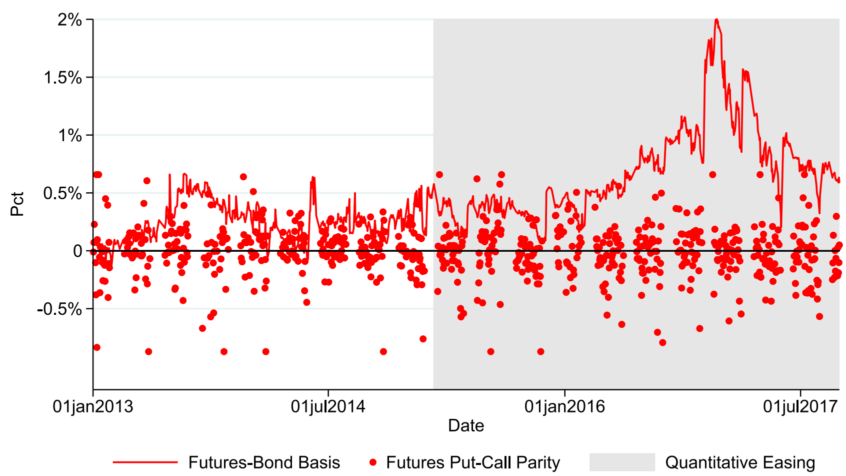

Fig. 9. Put-call parity for options on bund futures: This figure shows the time series of the deviations from the put–call parity for Bund futures options, defined as $PutCallParity_{k,t,T} = (\hat{F}(t,T) - F(t,T)) \cdot e^{-r_t \cdot (T-t)}$, the discounted difference between the option-implied futures price $\hat{F}(t,T) = e^{r_t \cdot (T-t)}(c(k,t,T) - p(k,t,T)) + k$ and the corresponding traded price, $F(t,T)$, where $c(k,t,T)$ ($p(k,t,T)$) is the price at time t of a call (put) option with expiry date T and strike price k written on a futures contract with delivery date T and price $F(t,T)$. r_t is the risk-free rate. We express the deviations as annualized returns. We match each trade of a call option with a transaction of a put option with the same delivery date and strike price, if the two trades took place within the same minute of a given trading day. We only consider options for which the expiry day is the same as the delivery date of the underlying futures contract. We aggregate the mispricing observations to create a daily put–call parity average deviation series. We report $Basis_{it}$ for Germany, for reference. We obtain data for Bund futures option from Eurex. The sample extends from January 2013 to September 2017. The QE period when the ECB was purchasing bonds is shaded in gray and starts in March 2015.

purchases amount and measures of market functioning is not a significant concern; second, we show that market functioning and friction variables do not exhibit non-stationarity and that our specifications are robust to allowing for richer dynamics.

If central banks conditioned their decision on whether or how intensely to engage in quantitative easing on market functioning, our analyses could suffer from endogeneity. We believe such risk is minimal, given that the rate of purchases does not vary considerably over time and that the allocation of purchases within Euro-zone countries is dictated by fixed capital keys. However, we can address the concern directly by using the instrumental variable approach developed by Koijen et al. (2021). They address the endogeneity between bond yields and investors' demand by developing an instrument for shocks to the Eurozone treasury supply, based on the ECB's policy announcements and capital keys.

Every quarter, they calculate the total amount of bonds that, by the end of QE, will be held at the ECB, based on the most recent announcement by the central bank. Estimations are revised as the overall size or duration of the program are updated. The total amount is then allocated across Euro-zone countries based on the ECB's capital keys. This approach allows us to circumvent the contemporaneity concern between purchases and market functioning, as purchases are announced well in advanced of the observed market functionig measures and allocation across countries is based on rules pre-dating the QE implementation.[18]

Figure IA-13 of the Internet Appendix shows the estimated series of maximum expected bond holdings by the ECB. We repeat the analysis in Tables 5 and 6 and instrument (replace) $ECB^{\%}_{it}$ with the instrumental variable $\widehat{ECB}^{\%}_{it}$ developed by Koijen et al. (2021). We report the results of the instrumental variable (reduced form) estimation in Table IA-7 (IA-8) of the Internet Appendix. Comparing the instrumental variable results in Table IA-7 with the baseline shows that the parameters are vastly unchanged, in both magnitude and statistical significant. Thus, we find little support for potential endogeneity concerns, in our setting.

[18] We thank Benoît Nguyen for the data, and Annette Vissing-Jørgensen for suggesting this analysis.

A second robustness check we conduct is to verify the stationarity of the variables of interest, as regressions including unit roots can lead to spurious results. Given that for any stationary process there exist a unit root process that is impossible to distinguish from the stationary representation (Hamilton, 1994, p. 445), we perform Dickey–Fuller tests for the presence of unit roots, following Choi (2001) to accommodate the panel data structure. At the bottom of Tables IA-9 and IA-10 of the Internet Appendix we report the results for the variables representing trading and funding frictions, and market efficiency, respectively. All tests reject the null hypothesis of presence of a unit root.

Finally, we want to ensure that our conclusions are robust to accounting for autocorrelation. In Table IA-9 of the Internet Appendix we replicate the analysis from Tables 2, 3, and 4, including the lagged dependent variable as regressor. We do the same with Table 5 and report the results in Panels A and B of Table IA-10 of the Internet Appendix, where we include the frictions as regressors in the latter, but not the former. While the point-estimate may differ from the earlier analyses, the statistical significance of the variable of interest is mostly unchanged.

6. Term-structure and swap spread arbitrage

In the previous sections, we focused narrowly on the pricing relation between bond and futures to document the effect of QE on the interest rate price-discovery process. However, any other arbitrage relation involving sovereign bonds would also be affected by the worsening of the frictions shown in Section 4. In this section, we show that our results hold more generally by considering the two strategies among the fixed-income arbitrages detailed in Duarte et al. (2007) that are applicable to the treasury market: the term structure and swap spread arbitrage.

To profit from a relative mispricing in the term structure, an arbitrageur would buy underpriced bonds and sell overpriced bonds, incurring transaction and funding costs. We then need to establish that the trading frictions we identified worsened for the average bond, not just the CTD, as QE purchases targeted all treasuries. We repeat the analyses from Tables 2, 3, and 4 in a sample that includes all 204 Italian and German long-term, coupon-bearing bonds. To account for bond-invariant characteristics, we include bond-fixed effects. We cluster standard errors two-way, by bond and date. Table 8 shows that market and funding illiquidity worsened for all bonds, not just the CTD, when their scarcity increased.

To quantify the inefficient functioning within the bond market, we fit a Nelson–Siegel model for each day in our sample, and calculate the root mean squared distance between the average daily market yields and the model-implied yields (the noise measure in Hu et al., 2013). For the swap spread arbitrage, we report the difference between the spread of a 5-year Eonia swap and the 5-year yield from the interpolated German curve.[19] As with $Basis_{it}$, our objective here is not to capture arbitrage profits, but rather to focus on the effect of the increase in frictions that followed QE.

We report the daily term-structure noise and swap spread measures in Fig. 10. Similar to the futures-bond example, these alternative market functioning measures increased during the QE period, as scarcity contributed to the collateral value of treasuries, and decrease as market participants resorted to the CCSLF. In Table 9, we repeat the analyses in Table 6 using these variables, finding similar evidence. While an in-depth analysis of these alternative trades is beyond the scope of this paper, the results in this section offer an example of the far-reaching consequences of QE on the price discovery process for interest rates.

[19] For the swap spread, we focus on the German curve, to limit the sovereign credit risk in the strategy. The same concern does not apply to a term-structure play, as it would have a net zero credit exposure.

Table 8
Quantitative easing effects on trading and shorting costs: This table shows the results for the regression of trading and shorting costs on the fraction of bonds of that country that are held at the ECB, $ECB^{\%}_{it}$, for a sample including all coupon-bearing Treasury bonds issued by Germany and Italy. The dependent variable in Specifications 1 is the bid–ask spread for bond i on day t, BA_{it}; the dependent variable in Specification 2 is the bond's repo specialness, $Specialness_{it}$, calculated as the difference between the European general collateral repo rate and the transaction volume-weighted special repo rate for i on day t; the dependent variable in Specification 3 is $SpecialnessRange_{it}$, the interquartile spread in the distribution of specialness for repo transactions involving bond i on day t. We include bond-fixed effects in all specifications. We control for: the volatility of the bond returns, σ_{it}; the bond's traded volume, $Volume_{it}$, in billions; year- and quarter-end dummies; and the bond's bid–ask spread, BA_{it}. We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are two-way clustered at the bond and day level. The sample is based on high-frequency quotes from 148,630 bond-days in our sample for the two countries, Germany and Italy, from January 2013 to September 2017. Bond price data and bond characteristics are obtained from MTS. Repo transactions data are provided by the MTS Group and BrokerTec.

	(1) BA_{it}	(2) $Specialness_{it}$	(3) $SpecialnessRange_{it}$
$ECB^{\%}_{it}$	0.498***	0.971***	0.129***
	(7.744)	(15.078)	(9.087)
σ_{it}	0.112***	0.016***	0.004***
	(18.599)	(3.796)	(4.161)
$Volume_{it}$	−0.172***		
	(−9.025)		
BA_{it}		0.004	0.004
		(0.187)	(0.830)
$YearEnd_t$	0.070***	0.079***	0.028***
	(7.272)	(4.065)	(3.328)
$QuarterEnd_t$	−0.004	0.006	0.018***
	(−1.159)	(0.681)	(5.881)
Adj. R^2	0.826	0.581	0.216
Obs	148 630	148 630	148 630
Bond FE	Yes	Yes	Yes

7. Discussion

In the previous sections, we show that the ECB's purchases of treasuries impaired market quality by making these bonds unavailable, thus reducing their market float. Large purchases of treasuries, however, are not unique to central banks, as buy-and-hold investors such as pension funds and insurance companies similarly hold them in large amounts and for long investment horizons (Fang et al., 2022; Chen et al., 2023; Eren et al., 2023). This begs the question of what makes QE purchases by the central bank unique. There are at least three reasons why we would not expect the same results to occur had the purchases been made by other long-horizon investors.

First, the ECB's approach to securities lending, prior to the CCSLF, is unique among buy-and-hold investors. Unlike the ECB, other buy-and-hold investors like pension funds and insurance companies actively lend out their holdings. Since lending securities (against cash) decreases scarcity, we would not expect to observe the same disruption in market functioning if large purchases were conducted by other buy-and-hold investors, who consistently engage in securities lending.[20]

[20] The extant literature shows that buy-and-hold investors are quite active in the market for securities lending. The International Security Lending Organization (2021) reports that 28% of all securities on loan are lent by pension funds and insurance companies. Similarly, Foley-Fisher et al. (2019) show that the vast majority of (corporate) bond lending originates from the holdings of insurance companies and pension funds, for whom securities lending is a

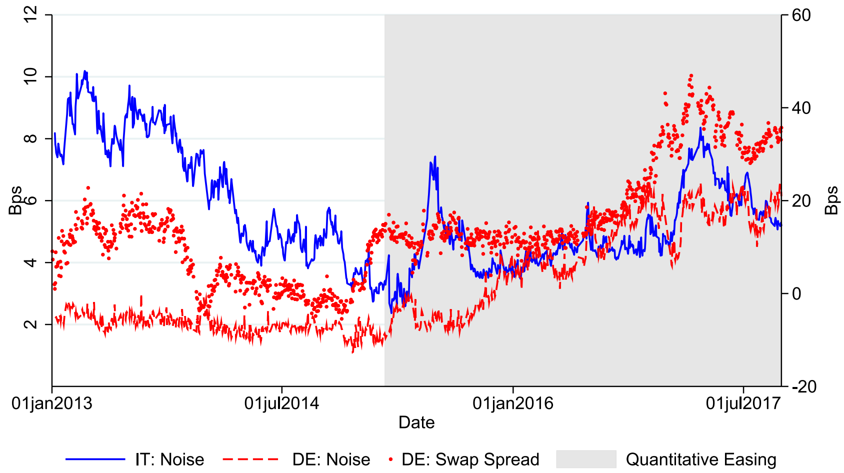

Fig. 10. Cross-maturity mispricing and the swap spread: This figure shows the time series of a measure of arbitrage opportunities across bonds of different maturities, for the German and Italian market, in red and blue, respectively (left y-axis). This measure corresponds to "noise" measure developed by Hu et al. (2013), which we calculate by fitting a Nelson–Siegel model to each day in our sample, and calculating the root mean squared distance between the average daily market yields and the model-implied yields. Similar to Hu et al. (2013), while we fit the model on every bond with more than one month to maturity, we calculate the noise measure only based on bonds with more than one year to maturity. We also plot the interest rate swap-Treasury spread, calculated as the 5-year spread for an EONIA-based swap and the corresponding constant-maturity yield of a hypothetical bond issued by Germany (right y-axis). We obtain 1105 observations for each country, based on a total universe of 164 bonds, or about 44 bonds on average per country/day. Bond data are obtained from the MTS group. Our sample extends from January 2013 to September 2017. The QE period when the ECB was purchasing bonds is shaded in gray and starts in March 2015. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 9
Quantitative easing effects on fixed-income arbitrages: This table shows the results for the regression of fixed-income arbitrage bases on the fraction of bonds of that country that are held at the ECB, $ECB^{\%}_{it}$. The dependent variable in Specifications 1 and 2 is the "noise" measure developed by Hu et al. (2013), which we calculate by fitting a Nelson–Siegel model to each day in our sample, and calculating the root mean squared distance between the average daily market yields and the model-implied yields. Similar to Hu et al. (2013), while we fit the model on every bond with more than one month to maturity, we calculate the noise measure only based on bonds with more than one year to maturity. The dependent variable in Specification 3 is the interest rate swap-Treasury spread, calculated as the 5-year spread for an EONIA-based swap and the corresponding constant-maturity yield of a hypothetical bond issued by Germany. The main explanatory variable is $ECB^{\%}_{it}$, the fraction of bonds held at the ECB, interacted with $CCSLF_t$, a dummy that is one after the ECB implemented a cash-collateralized securities lending facility, and zero otherwise. Specification 1 and 3 (2) use German (Italian) data. We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors clustered at the futures delivery level. The data sample covers the January 2013 to September 2017 period. Bond price data and bond characteristics are obtained from MTS. Interest rate swap data are obtained from Bloomberg.

	(1) $Noise_{it}$	(2) $Noise_{it}$	(3) $SwapSpread_{it}$
$ECB^{\%}_{it}$	0.002***	−0.001	0.948***
	(19.643)	(−0.956)	(4.139)
$CCSLF_t \times ECB^{\%}_{it}$	−0.002***	−0.002	−1.740***
	(−3.542)	(−0.563)	(−3.642)
$CCSLF_t$	0.000**	0.000	0.429***
	(2.372)	(1.107)	(5.070)
$YearEnd_t$	0.000	0.000	−0.033
	(1.180)	(−1.703)	(−0.840)
$QuarterEnd_t$	0.000	0.000	0.010
	(1.456)	(−0.131)	(1.680)
Adj. R^2	0.877	0.101	0.770
Obs	1105	1104	1092

Second, a significant share of the assets held by the ECB was, in fact, purchased *from* other buy-and-hold investors. To show this, we obtain data from the ECB's Government Finance Statistics dataset, which details the holder composition of the aggregate European sovereign bond market. We plot the holdings data in Figure IA-14 of the Internet Appendix for Germany in Panel (a), Italy in Panel (b), and in aggregate those for the Eurozone in Panel (c). The data show that holdings were virtually unchanged across investors for the European sovereign bond market, from 2006 up to 2015. During the QE period, however, the market experienced significant transfers between holder types, mostly from foreign investors—who are considered buy-and-hold or "inelastic" investors, together with insurance companies and pension funds—to the ECB (Arrata et al., 2020; Koijen et al., 2021).

Third, unlike other investors, the ECB lacks a profit motive, which impacts its purchase strategy in two ways. First, the central bank is required to purchase a fairly rigid combination of bonds (dictated by the member countries' populations and size, and, within each country, by its outstanding debt maturity composition), regardless of how expensive or special they are. Unlike the ECB, insurance companies and other buy-and-hold institutions are price-sensitive: For example, an insurance company can decide not to purchase a security that is highly sought after on the repo market, or is overpriced in their view, as it can easily obtain a similar exposure and regulatory alleviation by purchasing a cheaper close substitute. The ECB, on the other hand, needs to abide by an exogenously-given mandate, resulting in purchases of even very special bonds, which contributes to further increasing their specialness and, thus, worsening overall market functioning. A second channel through which the lack of a profit motive may contribute to our findings relates again to the securities lending market. Insurance companies and other similar investors would not forego the potential additional profit from securities lending, and would thus make their portfolios potentially available to the market. The central bank, on the other hand, is not driven by profit and accordingly decided not to lend out its securities in the regime before the implementation of the CCSLF.

The easing of scarcity that followed the implementation of the CCSLF shows that the central bank already possesses an effective tool to improve market functioning. The policy recommendation that follows

potential source of wholesale funding that allows them to boost the overall return on their asset portfolio (Foley-Fisher et al., 2016).

Table A.1
Cheapest-to-deliver bonds: This table reports, per each contract delivery and country in our sample, the International Securities Identification Number (ISIN) of the bond we identify as the cheapest to deliver. We report the frequency, in percentage terms of trading minutes per contract, for which the bond was the actual CTD (% CTD). We report the percentage of physically settled contracts that were settled with the bond we identify as the CTD (% of Delivered). Data on bond prices and repo rates employed to calculate the frequency of the CTD status of bonds are obtained from the MTS group and BrokerTec. Data on the prices of futures contracts and the fraction of physically settled contracts are obtained from Eurex.

Delivery	Germany			IT		
	Bond	% CTD	% of delivered	Bond	% CTD	% of delivered
201303	DE0001135465	99.924%	100.000%	IT0004848831	99.801%	100.000%
201306	DE0001135465	99.669%	100.000%	IT0004848831	67.324%	100.000%
201309	DE0001135473	99.901%	100.000%	IT0004848831	98.535%	100.000%
201312	DE0001135473	99.966%	100.000%	IT0004848831	89.672%	77.664%
201403	DE0001102309	99.926%	100.000%	IT0004848831	99.808%	100.000%
201406	DE0001102309	99.965%	100.000%	IT0004898034	99.866%	98.753%
201409	DE0001102325	83.059%	100.000%	IT0004898034	99.894%	100.000%
201412	DE0001102325	99.966%	100.000%	IT0004356843	99.747%	100.000%
201503	DE0001102333	99.654%	99.934%	IT0004953417	99.532%	100.000%
201506	DE0001102333	99.910%	100.000%	IT0004953417	99.399%	100.000%
201509	DE0001102358	99.816%	99.751%	IT0004513641	98.873%	100.000%
201512	DE0001102366	99.562%	100.000%	IT0004513641	76.522%	19.908%
201603	DE0001102374	99.808%	100.000%	IT0004513641	99.657%	100.000%
201606	DE0001102374	99.059%	100.000%	IT0004513641	99.872%	100.000%
201609	DE0001102382	98.619%	100.000%	IT0004644735	99.895%	100.000%
201612	DE0001102382	99.519%	100.000%	IT0004644735	99.981%	100.000%
201703	DE0001102390	99.855%	100.000%	IT0004644735	99.935%	100.000%
201706	DE0001102390	99.851%	100.000%	IT0004644735	99.897%	100.000%
201709	DE0001102408	99.962%	99.389%	IT0004889033	99.893%	100.000%
201712	DE0001102408	99.942%	100.000%	IT0004889033	99.793%	99.978%
Average		98.897%	99.954%		96.395%	94.815%
Median		99.853%	100.000%		99.797%	100.000%

from our analysis is for the ECB to adjust the availability of safe asset collateral on loan to improve market functioning as and when the need arises. The adjustment can be achieved in several ways: by lending a larger amount of its holdings, by increasing institution-specific security borrowing limits, by improving the pricing of its facilities, or by allowing non-banks to access the SLF. In sum, we propose that the central bank consider securities lending as a second lever in its QE toolbox, one aimed at containing the market quality costs that arise from the other lever, outright market purchases.

While these additional policy measures would improve market functioning, we doubt that they would affect markedly the main objective of QE, i.e., the reduction of the term premium. First, scarcity is one of several channels through which purchases affect bond prices (Krishnamurthy and Vissing-Jorgensen, 2011, 2013; Krishnamurthy et al., 2018): To the extent that market functioning does not worsen through these other channels, the central bank can impact yields while maintaining market quality. Second, the discretion we recommend for the implementation of securities lending means that the quantity of bonds lent via CCSLF can be kept far lower than the amount held by the ECB, improving market functioning while still allowing for safe assets to be somewhat scarce. Facilities like the CCSLF allow the central bank to calibrate the trade-off between pricing and market quality, and select the optimal level of scarcity.

8. Conclusions

Since the fallout from the Great Recession, central banks have routinely and successfully turned to Quantitative Easing (QE) to stimulate the economy. We show that implementing these interventions involves a necessary tension: While treasury scarcity reduces their yields, it impedes the price discovery process at play in the market for interest rates. It increases the transaction, funding, and carry costs involved in the arbitrage mechanisms that keep interest rates aligned across markets.

Focusing on the relation between treasury bonds and futures, we show a significant deterioration in the return correlation and price differential between otherwise identical assets. We extend the analysis to the term-structure and swap spread arbitrages and demonstrate that other pricing relations that include treasuries are similarly disrupted. As a conterfactual, we show that arbitrage relations involving only interest rates derivatives were as efficient before as after QE, since these securities were not made scarce.

Our findings point to the risk of market inefficiency and imperfect monetary policy transmission across markets, supporting policymakers' concerns regarding the effect they have on price discovery. However, we show that the exogenous policy change that allowed market participants to borrow the securities held at the ECB against cash provides an effective tool to modulate scarcity and restore market efficiency.

CRediT authorship contribution statement

Loriana Pelizzon: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marti G. Subrahmanyam:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Davide Tomio:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors acknowledge that they have read and agree to the JFE's submission guidelines and disclosure policies. The authors have no conflict of interest to disclose regarding the topics covered in this study or the findings therein.

In previous years, Tomio received funding for scholarly work from the FRIC Center at the Copenhagen Business School, the Volkswagen Foundation, and the Mayo Center for Asset Management at the University of Virginia.

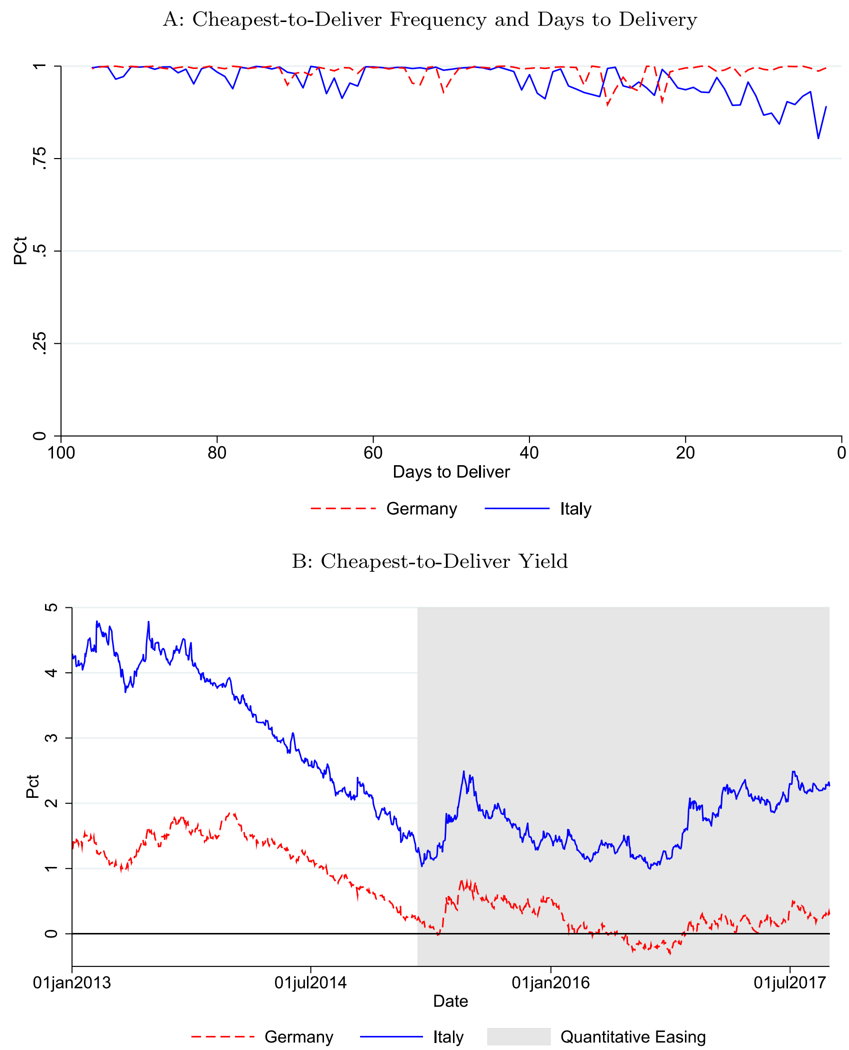

Fig. A.1. Cheapest-to-deliver frequency, days to delivery, and yield: Panel A of this figure shows the frequency the bond we identify as CTD has the smallest basis at different times during the life of the futures contract, averaged across all 20 contracts in our sample, and Panel B shows the yield to maturity of the bond we identify as CTD. We report the amounts separately for Germany (in red) and Italy (in blue). To determine how often the bond we identify as CTD indeed has the smallest basis, we calculate the mispricing for each deliverable bond in every trading minute in our sample, following Eq. (1), and identify the CTD bond for the whole contract. We report in Panel A the average frequency with which CTD bonds had the smallest basis over the three-month life of the contracts. The sample we employ is based on high-frequency quotes from 1105 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to September 2017. Bond price data and bond characteristics are obtained from MTS and futures data are obtained for the Eurex market via Thomson Reuters. Repo transactions data are provided by the MTS Group and BrokerTec. The QE period (i.e., when the ECB was purchasing bonds) is shaded in gray in Panel B and starts in March 2015. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Appendix A. Identification of the CTD bond

In the body of the paper, we focus the bond-market analysis on a single bond per country-day (i.e., the CTD bond that the short futures position is most likely to deliver). We identify the CTD bond for each contract following the calculations laid out in Sections 2.3 and 3. That is, we calculate the mispricing between each bond and the corresponding futures contract as per Eq. (1), for every trading minute of the life of the contract, and designate as CTD the bond for which the basis is smallest the majority of the time. While, in theory, the identity of the CTD bond could change through the life of the contract, because of changes in the shape of the yield curve, or in the set of bonds eligible for delivery, such uncertainty is minimal in the sample we consider. In Table A.1, we list the CTD bond per each contract in our sample, and show the percentage of minutes in the three-month contract duration that the bond we identify as CTD is indeed the cheapest among all deliverable bonds (% of CTD). We also report the percentage of contracts that were physically settled with the CTD bond (% of Delivered).

As shown in the table, the bond we identify as the CTD for a given contract is, on average, the one with the smallest basis 98.92% (95.67%) of the time for Germany (Italy), demonstrating that the uncertainty on the identity of the CTD was insignificant. Moreover, when the short futures positions holder decides to physically settle their positions, they do so using the CTD bond 99.98% of the time for Germany (93.90% for Italy). As the short position could deliver any of the bonds in the deliverable basket, the fact that the CTD bond is delivered in the overwhelming majority of cases further supports our identification. This clear identification of the CTD bond also suggests that the Bund and BTP futures markets are not subject to squeeze potential in the period we consider. Merrick et al. (2005) study the strategic trading around the delivery date of bond futures for the UK/Gilt market, and defines a full squeeze as the event that the CTD and the next CTD bond have the same (adjusted) price. If a squeeze happened in our sample, therefore, we should observe uncertainty as to the identity of the CTD bond, which is not the case in our data.

To check whether the identity of the CTD bond is known to market participants at the time of trade and not only ex-post, we plot the

Table B.1

Descriptive statistics: This table shows the distribution of CTD bond-specific variables, together with a host country-specific variables. Variables for Italian bonds are shown in Panel A. The corresponding quantities for German bonds are shown in Panel B. BA_t is the CTD bond bid–ask spread, in euros, σ_{it} is its return volatility, both based on observations sampled at a one-minute frequency. We calculate a bond's yield, $Yield_t$, from its average daily price, in percentage points. $Specialness_{it}$ is the CTD bond daily volume-weighted average repo rate for overnight transactions, in percentage points, and $SpecialnessRange_{it}$ ($SpecialnessVol_{it}$) is the repo specialness's interquartile spread (standard deviation), also in percentage points. $SpecialnessSlope_{it}$ is the country-specific difference between the average specialness for trades with a term of five days or longer and the average specialness for over-night trades. The table also shows the distribution for country-specific variables, at the bottom of each panel, such as the fraction of bonds held at the ECB as a result of its QE, $ECB^{\%}_{it}$, and the futures-bond basis $Basis_{it}$, in percentage points, as in Eq. (1). We also the basis once trading and funding costs are taken into consideration, $TradeBasis_{it}$. $Corr_{it}$ is the one-minute return correlation between the futures contract and an equally-weighted portfolio of deliverable bonds. $ImpliedRepo_{it}$ is calculated as the repo rate such that that the forward bond price in Eq. (1) equals the futures equivalent price. We subtract the ECB's deposit facility rate, to account for discrete changes in policy rates. Data on the ECB purchases were obtained from the ECB's website, and the amounts of sovereign bonds outstanding were obtained from the websites of national central banks. The sample is based on high-frequency quotes from 1057 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to September 2017. Bond price data and bond characteristics are obtained from MTS. Futures data are obtained for the Eurex market via Thomson Reuters. Repo transactions data are provided by MTS and BrokerTec.

Panel A: Italy								
	Obs	Mean	Std	P5	P25	Median	P75	P95
BA_{it}	1104	0.095	0.042	0.048	0.070	0.088	0.112	0.160
σ_{it}	1104	1.239	0.502	0.690	0.907	1.112	1.426	2.208
$Yield_{it}$	1104	2.419	1.078	1.159	1.521	2.111	3.253	4.384
$Specialness_{it}$	1103	0.073	0.167	−0.082	−0.019	0.016	0.140	0.361
$Spec.Range_{it}$	1103	0.045	0.052	0.005	0.015	0.028	0.058	0.135
$Spec.Vol_{it}$	1100	0.040	0.034	0.008	0.017	0.031	0.052	0.102
$Spec.Slope_{it}$	1092	−0.020	0.041	−0.071	−0.041	−0.022	−0.002	0.043
$ECB^{\%}_{it}$	1104	0.035	0.043	0.000	0.000	0.010	0.067	0.119
$Basis_{it}$	1104	0.001	0.004	−0.003	−0.001	0.000	0.004	0.010
$TradeBasis_{it}$	1103	−0.003	0.004	−0.011	−0.006	−0.003	−0.001	0.002
$Corr_{it}$	1097	0.905	0.045	0.815	0.883	0.917	0.937	0.957
$ImpliedRepo_{it}$	1104	−0.043	0.366	−0.765	−0.262	0.043	0.226	0.411
Panel B: Germany								
	Obs	Mean	Std	P5	P25	Median	P75	P95
BA_{it}	1105	0.054	0.022	0.033	0.042	0.050	0.058	0.097
σ_{it}	1105	1.040	0.305	0.688	0.842	0.979	1.158	1.574
$Yield_{it}$	1021	0.683	0.602	−0.173	0.157	0.535	1.279	1.649
$Specialness_{it}$	1105	0.286	0.367	0.022	0.068	0.172	0.442	0.716
$Spec.Range_{it}$	1105	0.072	0.148	0.010	0.020	0.040	0.090	0.190
$Spec.Vol_{it}$	1104	0.060	0.120	0.007	0.019	0.038	0.075	0.140
$Spec.Slope_{it}$	714	0.059	0.106	−0.072	−0.007	0.045	0.103	0.245
$ECB^{\%}_{it}$	1105	0.058	0.072	0.000	0.000	0.017	0.111	0.204
$Basis_{it}$	1105	0.005	0.004	0.001	0.002	0.004	0.007	0.012
$TradeBasis_{it}$	1105	0.000	0.003	−0.005	−0.002	0.000	0.001	0.004
$Corr_{it}$	1098	0.973	0.017	0.940	0.967	0.978	0.985	0.990
$ImpliedRepo_{it}$	1105	−0.388	0.406	−1.160	−0.614	−0.303	−0.086	0.072

average frequency that the bond we identify as CTD has the smallest basis at different times during the life of the futures contract in Panel A of Fig. A.1. The graph shows that the CTD has the smallest basis more than 95% of time, on average, already on the first day of trading (i.e., when there are 90 days to delivery), confirming the minuscule degree of uncertainty regarding the identity of the CTD.

The CTD bond is determined as the bond with the smallest basis. Considering Eq. (1), it is clear that, everything else constant, the higher the conversion factor of a bond, the lower the associated basis. Conversion factors are calculated with complex formulas that can be found on the Eurex website, but can be approximated with high precision as the price the bond would have at delivery if the yield curve was flat at 6%, scaled by its face value. If yields are below 6%, as is the case during the period we consider, the conversion factor is higher, the smaller is the duration of the CTD bond, to a first approximation. Conversely, if yields are above 6%, the CTD bond will be that with the largest duration. It follows that the likelihood of the CTD's identity changing during the life of the contract is the highest when bond yields are near 6%. Panel B of Fig. A.1 shows the yield of the CTD bond in the period we consider. The yields are, generally, far from 6%, confirming that the identity of the CTD is known with certainty by market participants. The optionality to deliver the cheapest bond, called the quality option, is priced in the futures contract, and can be valued following standard option-pricing models. While our calculations eschew the quantification of the value of such an option, its value would be very small, given the low yield level in relation to the 6% notional coupon, and as confirmed by the extremely high fraction of time that the bond we identify as CTD is indeed the CTD (i.e., the switching of the CTD status among deliverable bonds is exceedingly rare).

Appendix B. Descriptive statistics

In this section, we report the descriptive statistics of the variable we employ in our analysis. Table B.1 shows the number of observations, average, standard deviation, and fifth, 25th, 50th, 75th, and 95th percentiles of the left- and right-hand-side variables in our specifications separately for Italy and Germany in Panels A and B, respectively. The top part of each panel features CTD bond characteristics (such as its yield to maturity, liquidity, and repo specialness), while the bottom part of each panel shows measures of market efficiency (such as the basis, 1-min correlation, implied repo and tradeable basis) and the aggregate amount of bonds held at the ECB per country, as a fraction of their outstanding amount.

We calculate the bonds' best bid and ask prices, and the corresponding bid–ask spreads, at a one-minute frequency. We average the spreads at a daily level to calculate the bonds' illiquidity, BA_{it}, in euros, and we use the midquote to calculate the daily one-minute return standard deviation, σ_{it}, which we express in basis points. We average the midquote throughout the day to calculate the bonds' yield, $Yield_{it}$, in percentage points. In our analyses, we employ bond-specific characteristics, such as the bond's outstanding amount $AmtIssued_i$, in billions of euros. Since the identity of the CTD bond varies between contracts (see Table A.1 for the full list of CTD bonds by delivery), the variable $AmtIssued_{it}$ will change discretely as the CTD changes. We calculate the volume of trading, $Volume_{it}$, as the amount traded on the MTS platform for the CTD bond i on day t, in billions of euros. We show in Table B.1 the descriptive statistics for repo transactions on CTD bonds. $Specialness_{it}$ is the transaction volume-weighted specialness for overnight repo transactions on CTD bond i on day t, calculated with respect to the GC rate, in percentage points, while $SpecialnessRange_{it}$ is the interquartile range of that distribution, in percentage points, and $SpecialnessVol_{it}$ is the corresponding standard deviation, also in percentage points. $SpecialnessSlope_{it}$ is the country-specific difference between the average specialness for trades with a term of five days or longer, and the average specialness for over-night trades, in percentage points.

The bottom variables in the panel represent measures of interest rate market functioning and bond scarcity: $Basis_{it}$, $Corr_{it}$, $ImpliedRepo_{it}$ and $TradeBasis_{it}$ which are described in Sections 3 and 5. $ECB^{\%}_{it}$ measures the fraction of bonds held at the ECB, i.e., the stock of purchases divided by the outstanding debt amount.

Appendix C. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jfineco.2025.104004.

Data availability

Replication Code for Central Bank Driven Mispricing (Original data) (Mendeley Data)

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