Is the bond market competitive?

Evidence from the ECB's asset purchase programme*

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Abstract

We show that during the period of the Public Sector Purchase Program (PSPP) implemented by the Eurosystem, the prices of German sovereign bonds targeted by the PSPP increase predictably towards month-end and drop subsequently. We propose a sequential search-bargaining model that captures salient features of the implementation of the PSPP such as the commitment to buy within an explicit time horizon. The model can explain the predictable pattern as a result of imperfect competition between dealers that are counterparties to the Eurosystem. Motivated by the model's predictions, we show that the price pattern is more pronounced (a) for bonds that are targeted by the PSPP, (b) for monthly windows where the Eurosystem has fewer counterparties, and (c) for monthly windows where the Eurosystem targets a larger amount of purchases. We discuss the implications of our analysis for future purchase programs.

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Non-technical summary

This paper takes a research perspective on the question whether fixed monthly central bank purchase targets affect sovereign bond prices. It studies the question both empirically and theoretically, using German bund data from the early years (2015-2017) of the Eurosystems Public Sector Purchase Programme (PSPP).

The empirical analysis documents increased prices in the German government bond market at the end-of-month. The theory provides a potential explanation for this pattern with bond dealers' market power in over-the-counter (OTC) markets. When the central bank, as a large buy-and-hold investor, buys a fixed amount of bonds over a month, dealers quote higher prices at the end-of-month. As achieving the target towards the end-of-month becomes more pressing, the bargaining power of dealers vis-a-vis the central bank increases.

The German sovereign bond market provides a clear case study to test the theory for the following reasons. First, the German sovereign debt is the safe asset in the euro area and is the most liquid asset. Second, a unique feature of the PSPP is that the allocation of purchases across countries is based on the ECB capital key with each National Central Bank only buying bonds from its own country. Because Germany has the highest ECB capital key, approximately 27%, the PSPP purchases are substantially geared to this country providing an implicit monthly target. Third, the German sovereign bond market is not the largest one among the major euro area countries. As a result, the Eurosystem became the largest holder of German sovereign bonds in the euro area holding more than 24% of the outstanding amount at the end of 2017.

Empirical tests link end-of-month price pressure to purchases under the PSPP. First, purchased bonds show even lower yields towards month-ends. Importantly, while for eligible bonds the lowest point is reached at the end-of-month, for purchased bonds the lowest point is reached two days before the end-of-month. This coincides with the last day in a given month on which Eurosystem trades count towards the monthly purchase targets since it takes two trading days to settle the trade. Second, the pattern is significantly more pronounced when the Eurosystem targets larger purchase amounts in front-loading months to avoid trading during summer and end-of-year months (even though markets tend to be more liquid during these front-loading periods). Third, the price pattern is stronger in months in which trades are settled with fewer dealers and more pronounced around quarter-ends when dealers are more balance-sheet constrained due to regulatory requirements.

These findings by no means imply inefficient implementation by Eurosystem operational staff; rather, they stem from a non-competitive market situation. The analysis points to potential implications for the design of asset purchase programs, although a full cost-benefit analysis of such measures would still need to be conducted. First, the Eurosystem should consider moving away from committing to fixed euro notional purchases at fixed dates originally introduced to strengthen the perception that the Eurosytem was resolute in executing the PSPP. The implicit monthly purchase target for a large country as Germany can increase the price pressure effect by giving more bargaining power to dealers towards each end-of-month. One way to ease such a constraint could be to define the amount as a total envelope over a longer period similarly to the Pandemic Emergency Purchase Programme (PEPP). Second, the Eurosystem should consider moving towards trading on broader platforms open to a larger number of counterparties to encourage more competition from other natural sellers (such as large insurance companies or buy-side firms). Although some Eurosystem national central banks have used reverse auctions to target specific securities under the PSPP, one could imagine setting up regular auctions possibly via some centralized electronic trading platform at Eurosystem level as a useful trading mechanism to have in place. On this platform, all dealers, not limited to the national central banks counterparties, could supply their quantities available for purchase by the Eurosystem. Finally, the Eurosystem modified the PSPP eligibility criteria to face the shortage of German sovereign bond securities. Expanding the set of securities eligible for PSPP purchases at the end of 2016 increased the availability of targetable securities potentially limiting the bargaining power of dealers at the end-of-month.

1 Introduction

Following the great financial crisis, many central banks around the world have engaged in large scale asset purchases. The primary purpose of these asset purchases is the conduct of unconventional monetary policy and, as such, research has focused on whether and how these programs achieved the macro-economic goals of stimulating inflation and economic growth.[1] However, these purchases also constitute a unique opportunity to investigate the market microstructure of sovereign bond markets, which typically function over the counter (OTC) with a limited number of dealers playing a central role in the intermediation of trades. It is often argued that having specific dealers with unique prerogatives to trade governmental securities insures market liquidity and efficient and deep secondary markets. It is thus interesting to investigate whether the central banks engaging in these large purchases indeed buy securities at efficient prices. On the one hand, this is useful to better design the implementation of (future) purchase programs. On the other hand, it provides insight into the OTC structure organized around a limited number of liquidity providers, and specifically about whether this market structure achieves prices that approach competitive prices.

In this paper, we look at the Public Sector Purchase Program (PSPP) announced on January 22, 2015 by the European Central Bank (ECB). The initial size of the program was 60 billion euros per month from March 2015 to March 2016. The program was subsequently expanded to 80 billion euros per month until March 2017, followed by 60 billion euros per month until December 2017.

Even though the program mostly targeted the most liquid euro area sovereign bonds, we document systematic patterns in prices with yields (prices) of German government bonds steadily decreasing (increasing) before each month-end and recovering (decreasing) thereafter during the PSPP implementation from 2015 to 2017. Figure 3 displays the pronounced U-shaped pattern in bonds' yields. What could explain such a surprising price pattern?

We develop a simple theoretical search-bargaining model that incorporates salient features of the PSPP such as the commitment to buy within an explicit time horizon and shows that it can replicate the observed pattern as a result of imperfect competition among dealers that provide liquidity. In our model a single buyer (the central bank) contacts the same N dealers over a repeated number of trading rounds to purchase some finite number of securities.[2]

[1] See for example Koijen et al. (2021), Di Maggio, Kermani, and Palmer (2020), Gagnon et al. (2011).

[2] Our model builds on the insights of the consumer search literature, such as Weitzman (1979), Stahl (1989),

We assume that the central bank has a reservation price that is known to all dealers and that exceeds the cost to the dealers of providing the asset. The central bank contacts all dealers in every round, but each dealer provides a quote only with some probability, assumed to be strictly less than one to reflect the possible lack of available inventory of the targeted security (or the inability to locate the desired security at sufficient speed).[3] Dealers who provide a quote do so to maximize their expected profit from selling to the central bank over the T trading rounds. The central bank purchases securities so as to minimize its total expected cost for acquiring the targeted number of securities by T. We derive the equilibrium distribution of quoted prices by dealers, as well as the equilibrium average transaction prices at which the central bank will acquire targeted securities in every round.

The model generates increasing average transaction prices and price-dispersion as time approaches maturity. The intuition is that in every round contacted dealers are competing with other dealers contacted in that same round as well as with dealers that will be contacted in subsequent rounds. Therefore competition is highest the more rounds of trading are expected and the fewer securities the central bank wants to purchase. As maturity approaches, contacted dealers realize that they have increasing bargaining power and, in equilibrium, quote from a density whose mean is closer to the reservation price of the central bank. For intuition, consider the case where at most one dealer can quote a price in every round, then clearly in the last round any dealer, realizing that she is the only one quoting, would quote the maximum reservation price, thus extracting all the surplus. In earlier rounds, dealers experience more competition and thus quote from an equilibrium density that is closer to their cost. The central bank buys in every round at the lowest price quoted by any of the dealers, if that minimum price is lower than the expected minimum price that will be offered in subsequent rounds. In equilibrium, we observe that the average transaction price increases over the trading rounds as we approach maturity.

The model makes a number of other qualitative predictions that we can investigate in the data. First, we expect that the price pattern should be more pronounced the more market power the

Janssen, Moraga-Gonzalez, and Wildenbeest (2005), which have been applied to OTC markets by Duffie, Dworczak, and Zhu (2017) and Vogel (2020) among others. The aforementioned papers typically consider a single period search-matching game between a continuum of buyers and a finite number of sellers.

[3] Alternatively, this probability reflects the current purchase protocol in place, whereby the central bank only contacts a few (3-4) dealers from the full set at every trading rounds. We discuss the current trading protocol in Section 2.1.

dealers have, that is the larger the targeted asset purchases, the fewer the number of quoting dealers, and the more impatient the central bank is to fill its quota. Second, the model predicts that the cross-sectional variation in transaction prices and quotes should be larger as we approach the target date (the end-of-month in our data).

We test these predictions using data on the Eurosystem's PSSP from 2015 to 2017. We focus on the German government bonds for the following reasons: the German government debt is the "safe asset" in the euro area and is the most liquid (Corradin, Grimm, and Schwaab (2021)). Also, a unique feature of the PSPP is that the allocation of purchases across countries is based on the ECB capital key with each National Central Bank only buying bonds from its own country while the ECB purchases bonds from all countries (Hammermann et al. (2019), Bundesbank (2018)).[4] The ECB capital key is an equal-weighted average of GDP and population shares and is revised infrequently. Because Germany has the highest ECB capital key, approximately 27%, the PSPP purchases are substantially geared to this country providing an implicit monthly target.[5] As a result, the Eurosystem became the largest holder of German sovereign bonds in the euro area holding more than 24% of the outstanding amount at the end of 2017 (Bundesbank (2018)).

First, we find that during periods where the Eurosystem targets larger purchase amounts the price pattern is significantly more pronounced. To avoid the lower liquidity in summer months, the Eurosystem decided to front-load its purchases and purchase larger amounts during the May, June and November months than during July, August and December. This is particularly interesting since 'front-loading' of purchases was implemented to avoid trading during summer and end-of-year months which are typically more illiquid. It suggests that the pattern is not directly linked to bond market liquidity. Instead this finding is consistent with our model that a higher purchase target implies greater bargaining power of the dealers.

Second, we document that price pressure is stronger for the targeted bonds that are actually acquired in a day relative to the bonds that would be eligible but actually did not get purchased by the Eurosystem. Importantly, while for eligible bonds the lowest point is reached at the end-of-month, for purchased bonds the lowest point is reached two days before end-of-month. This coincides with the last day in a given month on which Eurosystem trades count towards the monthly

[4] More details on the PSPP implementation are given in Section 2.1.

[5] The other two major countries are France and Italy with a capital key of 20.7% and 18% respectively.

purchase targets since it takes two trading days to settle the trade. This suggests a direct causal link between the price pattern and the Eurosystem purchasing activity. When we study the determinants of the daily purchase decision for German sovereign bonds, we find that the decision is mainly affected by the eligibility criteria that are unique to the Eurosystem as an investor compared to other large investors.

Third, we find that the price pattern is significantly more pronounced in months where the Eurosystem trades with fewer counterparties, which is again consistent with the model implication that the fewer the counterparties that quote a price, the larger their individual bargaining power, and thus the larger the surplus they can extract.

Fourth, we find that the price pattern is much more pronounced around end of quarters. It is well-known that dealer banks are more balance-sheet constrained around end of quarters (Arrata et al. (2020), Corradin et al. (2020), Breckenfelder and Ivashina (2021) and Munyan (2017)), which might imply a lower degree of competition among dealers around end-of-quarters. Overall, our evidence seems consistent with our simple model of imperfect competition faced by the central bank bargaining with a few central dealers over a finite number of rounds.

Finally, we compute an expected shortfall to provide an estimate of the impact of bond prices increasing at the end of the month on the Eurosystem. The expected shortfall is a standard metric in market microstructure literature (Perold (1988)) to measure the extent to which markets are illiquid and does not imply a market loss for the Eurosystem.[6] Specifically, we compute the difference between the value of the total purchases in the last 10 days of each month and the value of the purchases executed at the mid-of-month prices. Based on our estimates, the impact due to the difference in prices of German sovereign bonds is on average euro 12.3 million per month of the market value of the securities purchased in the last 10 days of each month. The total yearly impact amounts to euro 148 million during our sample period.

Recent empirical literature has explored empirically the interactions between the PSPP and sovereign bond prices. Schlepper et al. (2020) find economically significant price impacts of the PSPP on German sovereign bonds using high-frequency inter-dealer data. Interestingly, they also document that transacting dealers quickly update bond quotes and the remaining dealers quickly follow suit indicating that the Eurosystem is an important player in the German sovereign bond

[6] See the discussion in Section 5.4.

market. Arrata et al. (2020) find economically significant price impacts of the PSPP on special repo rates. De Santis and Holm-Hadulla (2020) find that PSPP causes statistically significant and economically relevant temporary upward price impacts. Our paper has a different focus and investigates the interaction between the central bank purchase program design (i.e. monthly targets) and the market structure in the euro area sovereign bond markets.

Several papers have documented surprising seasonal price patterns in bond markets. Most notably Lou, Yan, and Zhang (2013) show that the US Treasury yields typically rise ahead of US Treasury auctions. These price concessions result in extra-profits for the dealers, who get to buy bonds at slightly depressed prices in perfectly predictable and repeated US Treasury auctions. They are typically justified as 'fair' compensation for the ware-housing risk faced by intermediaries with limited risk-bearing capacity, who need to hold the newly issued US Treasuries while looking for a counterparty. The idea is similar to the traditional inventory risk explanation of bid-ask spreads (Stoll (1978)). In our case, we observe an asymmetric pattern around large government bond purchases. This implies that dealers get to sell bonds at slightly "overvalued" prices to the Eurosystem. Since arguably the Eurosystem is taking risk off the balance sheet of banks it seems harder to explain why dealers should require an extra compensation to reduce their interest rate risk-exposure.[7]

Of course, arguably the Treasury bond ware-housing risk faced by dealers could be hedged quite effectively using Treasury bond futures, which could somewhat mitigate the traditional explanation for the price concession. An alternative explanation for the price concession observed during bond issuances in the French government bond market is offered in Sigaux (2020), who argues that the price concessions are also compensation for the uncertainty faced by dealers about the amount to be issued. In our case the purchased amount and target dates are public knowledge (i.e., the Eurosystem targets 60 billion euros in purchases by the end of every month during the PSPP).

Newman and Rierson (2004) document significant price concessions around large issuances in the European Telecom sector corporate bond market. They view these price concessions as compensation of ware-housing risk faced by the dealers who absorb the issuance. They also document

[7] One possibility is that banks without Bund inventory need to enter a reverse repo transaction to obtain the bond, in order to sell it to the Eurosystem. This may entail balance-sheet costs, which may affect dealers ability to intermediate (He, Nagel, and Song (2021)). While this may be the case for some banks, in aggregate European banks hold a large amount of euro area sovereign bonds. This may however contribute to lowering competition around end-of-quarters, consistent with our findings.

significant spill-over effects to other bonds, which is interpreted as resulting from the overall lower risk-bearing capacity of bond dealers. Interestingly, we find that the effect is much more pronounced for the bonds that are targeted in a given day than for bonds that are perfect substitutes from a risk-perspective, but not purchased in a given day.

Our results have two potential implications. First, the Eurosystem should consider moving away from committing to fixed euro notional purchases at fixed dates originally introduced to strengthen the perception that the ECB was resolute in executing the PSPP when announced on 22 January 2015 (Rostagno et al. (2021)). Having to fill the mandate for a large country as Germany by each end-of-month under the PSPP can increase the price pressure effect by giving more bargaining power to dealers towards each end-of-month. One way could be to define the amount as a total envelope over a longer period similarly to the ECB's Pandemic Emergency Purchase Programme (PEPP).

Second, if the temporary price pattern we identify around the public purchase is due to the non-competitive market structure as our model suggests, then the cost of the Eurosystem purchases are increased by a component that might be avoided modifying the current purchase method. The Eurosystem should consider moving towards trading on broader platforms open to a larger number of counterparties to encourage more competition from other natural sellers. Although some Eurosystem national central banks have used reverse auctions to target specific securities under the PSPP (Hammermann et al. (2019)), one could imagine setting up regular auctions possibly via some centralized electronic trading platform at Eurosystem level as a useful trading mechanism to have in place. On this platform, all dealers, not limited to the national central bank's counterparties, could supply their quantities available for purchase by the Eurosystem. This platform could be opened up to other large institutional investors (such as large insurance companies or buy-side firms) who might also be available to trade their inventory of fixed-income securities. Such a system might also be useful to help in times of severe stress when the central bank may have to act as a 'buyer of last resort,' as recently advocated by Duffie (2020), in his review of the failures of the US Treasury market structure during the March 2020 Covid-crisis induced US Treasury market upheaval. Duffie's argument is that with reduced dealer balance sheet capacity and with increased supply of US Treasury bonds, in times of stress when international holders of US Treasuries may want to liquidate their position, dealers' warehousing capacity may be limited and the central bank may have to step in, acting as a buyer of last resort, to maintain secondary market liquidity in US Treasury securities. Our results suggest that having a regular and centralized auction mechanism for the Eurosystem to engage in large scale bond purchases might also make sense in normal times. More research would be needed to be more specific. Also, a cost-benefit analysis would be critical to assess such auction designs and their usefulness for the Eurosystem.

Our paper is also related to An and Song (2020), who show that dealers strategically manage inventory and charge uncompetitive pricing to the US Federal Reserve bank in the agency MBS market and to Song and Zhu (2018) who document uncompetitive behavior among large dealers participating in the US Fed's QE auctions. Lastly, our findings about specific price patterns around Eurosystem purchases also resonate with the literature on 'slow-moving capital' (Duffie (2010)) or on 'inelastic markets' (Gabaix and Koijen (2021)), but the price patterns we find are unlikely to be driven by similar channels,[8] nor are they likely to be due to the 'adverse selection' channel of Kyle (1985) and Glosten and Milgrom (1985). Instead, we argue the evidence is more consistent with a "non-competitive" market structure channel, whereby dealers exploit some of the features of the purchase program implementation.

In the next section we present some institutional details about the PSPP and its implementation and show the evidence on the price impact of the Eurosystem purchases. Then we introduce a dynamic bargaining model that is consistent with the observed price pattern. Finally, we test further implications of the model and discuss some of its implications for the implementation of large scale asset purchases in OTC markets.

2 Setting and data

2.1 Institutional background of the Eurosystem's quantitative easing programme

On January 22, 2015 the ECB announced its expanded asset purchase program (APP). The APP is part of a package of policy measures that was initiated in mid-2014 to support the monetary policy transmission mechanism and provide monetary stimulus in an environment where interest

[8] Duffie (2010) argues that inattention by some investors leads supply shocks to have persistent and lasting price effects in a competitive rational expectations (RE)-model. Gabaix and Koijen (2021) argue that because some investors have some fixed mandates, the price-impact of orders of the unconstrained investors can have more dramatic 'permanent' price effects. Our findings are more of a temporary nature.

rates had fallen below zero.

The ECB governing council *ex ante* defined clear and observable monthly targets for how much to buy within a month.[9] Figure 1 plots the monthly volumes of the securities purchased under the APP. The continuous blue line shows the monthly target. Monthly purchases were conducted at an average pace of: 1) euro 60 billion from March 2015 until March 2016; 2) euro 80 billion from April 2016 until March 2017; 3) euro 60 billion from April 2017 to December 2017; 4) euro 30 billion from January 2018 to September 2018; and 5) euro 15 billion from October 2018 to December 2018.[10]

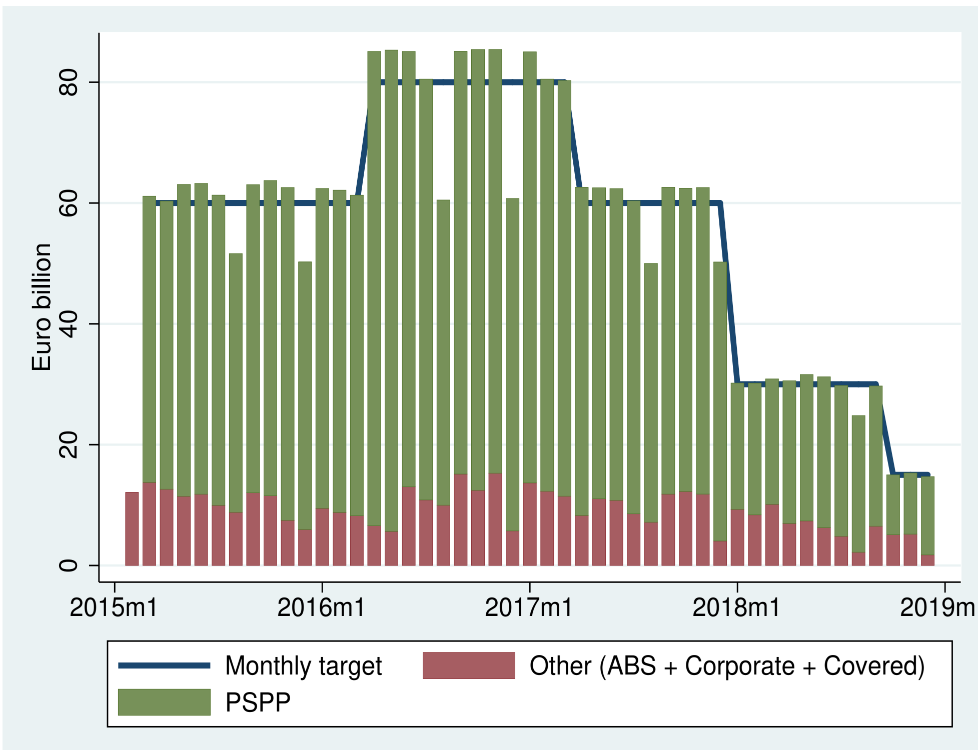


Figure 1. Average monthly purchases APP targets. Amounts in euro billions.

As shown in the figure the monthly purchases are close to the average monthly APP target but are below the target in specific periods, such as from mid-July to late August and in December. Purchase activity was front and back-loaded around these periods to account for seasonal patterns in fixed income market activity, such as the decline in bond market liquidity. In addition, monthly fluctuations can reflect the variability in the redemption and reinvestment profiles because the bond

[9] In all months, the purchase guidance was expressed in monthly totals, rather than in strict daily volumes, providing flexibility in the day-to-day execution of purchases.

[10] On 12 September 2019 the ECB Governing Council decided that net purchases will be restarted under the APP at a monthly pace of euro 20 billion as of 1 November 2019.

principal redemptions are reinvested in bonds issued by the same country and distributed over the calendar year.

The main part of the APP was the public sector purchase programme (PSPP) that accounts on average for almost 82% of the total net purchases (green bars in Figure 1).[11] The PSPP mainly targets bonds issued by euro area central governments, recognized agencies, and European institutions in the secondary market. The APP additionally includes the corporate sector purchase programme (CSPP), the asset-backed securities purchase programme (ABSPP), and the third covered bond purchase programme (CBPP3) (red bars in Figure 1).

While the PSPP is coordinated by the ECB, it is implemented in a decentralized way both by the ECB and by the National Central Banks (NCBs). That is, actual purchases are executed by the NCBs or by the ECB with their respective counterparties. When purchasing a bond, the executing central bank asks several of its counterparties to provide quotes. The offer is accepted if at least three counterparties offer executable quotes. The lowest price wins (see Hammermann et al. (2019)).

In this paper, we focus on the German sovereign bond market between March 9, 2015 and February 27, 2017 due to data availability for the following reasons. First, the German government debt is the "safe asset" in the euro area and is the most liquid (Corradin, Grimm, and Schwaab (2021)). Second, a unique feature of the PSPP is that the allocation of purchases across countries is based on the ECB capital key (Hammermann et al. (2019), Bundesbank (2018)), with NCBs focusing exclusively on purchases in their home market. The Eurosystem geared its monthly purchase PSPP allocation to align a country's share in the stock of PSPP purchases as closely as possible with the respective share of the ECB capital key providing an implied monthly target of purchases at country level as announced on January 22, 2015.[12] The capital keys are computed according to the share of each member state in the total population and aggregated gross domestic product of the European Union (EU), with each factor having equal weighting. Germany, as the largest economy and most populous country in the euro area, has the highest ECB capital key and

[11] Based on authors' calculation using public ECB data. See `https://www.ecb.europa.eu/mopo/implement/app/html/index.en.html`.

[12] The ECB Governing Council decided that "*Purchases of securities under the expanded asset purchase programme that are not covered by the ABSPP or CBPP3 will be allocated across issuers from the various euro area countries on the basis of the ECB's capital key.*" See `https://www.ecb.europa.eu/press/pr/date/2015/html/pr150122_1.en.html`

therefore has the largest allocation of the PSPP portfolio, approximately 26.3%, followed by France and Italy with a capital key of 20.7% and 18% respectively.

Figure 2 plots the monthly share of purchases on German securities over the total PSPP purchases (continuous blue line) and the Germany's ECB capital key (dashed red line) from 2015 to 2017. The figure is based on publicly available data published by the ECB every month when it provides the country break down.[13],[14] The figure clearly shows that the ECB capital key is a binding benchmark for Germany. The Eurosystem bought German securities each month, approximately euro 17.25 billion when the overall APP monthly target was euro 80 billion[15], and the monthly volume is a constant share of the overall PSPP monthly purchases and close to the Germany's ECB capital key.

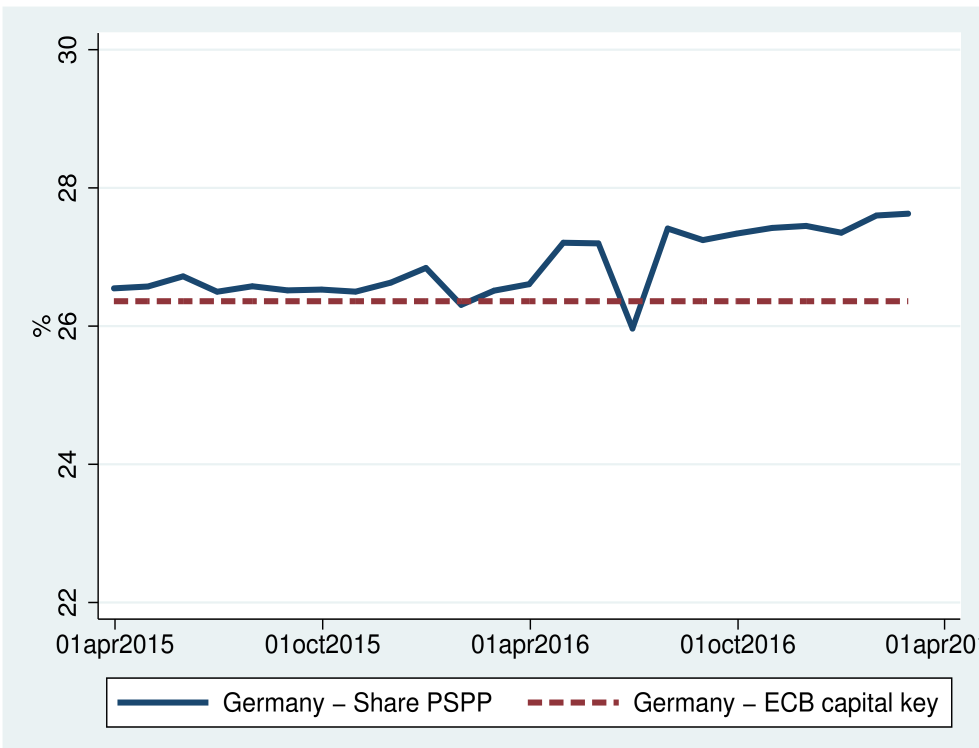


Figure 2. Monthly share of German securities purchased under the PSPP.

Third, the German sovereign bond market is not the largest one among the major euro area

[13] See `https://www.ecb.europa.eu/mopo/implement/app/html/index.en.html`.

[14] The country beak down data are used by market analysts to compute the implied (or theoretical) monthly target at country level or to compute the deviations from the ECB capital key. See for the example the BNP's report "ECB: The PSPP parameters" `https://economic-research.bnpparibas.com/html/en-US/ECB-PSPP-parameters-9/23/2016,29112`.

[15] Because the PSPP accounts on average for almost 82% of the total net purchases, we have $80 \times 0.82 \times 0.263 = 17.25$

countries with a relatively low supply of debt. Before the start of the PSPP, Germany had euro $1,398,475$ million of central government bonds, while France had euro $1,695,039$ million and Italy has euro $2,112,558$ million respectively.[16] It is also worth noting that the net supply of German government bonds is negative during our sample period, which tends to further narrow the availability of securities and the purchasing horizon for the PSPP (Paret and Weber (2019)). As a result, the Eurosystem became the largest holder of German sovereign bonds in the euro area due to the PSPP holding more than 24% of the outstanding amount at the end of 2017 (Bundesbank (2018)).

The Eurosystem modified the PSPP parameters to face up to the potential shortage of public securities, notably German. Securities purchased under the PSPP have to fulfill a set of eligibility criteria. First, the securities covered by the PSPP initially included nominal and inflation-linked central government bonds. On December 3, 2015 marketable debt instruments issued by regional and local governments located in the euro area were added to the list of eligible assets.[17] Expanding the set of securities eligible for PSPP purchases was intended to enhance the flexibility of the program and thereby support its implementation (Schlepper et al. (2020)). Second, the PSPP originally required the maturity of purchased bonds to be between 2 and 31 years. The maturity range of the PSPP was broadened by decreasing the minimum remaining maturity for eligible securities from two years to one year on January 19, 2017. Third, purchases could not exceed 33% (25%) of an issue (issuer).[18] The limit was relaxed in September 2015, allowing the Eurosystem to hold up to 33% of an issuer. Finally, the yield of bonds had to be above the ECB deposit facility rate, which was equal to -20bps at the launch of the programme. On January 19, 2017, the ECB governing council decided to relax this rule allowing further purchases of bonds with a yield below the deposit facility rate making numerous German government bonds eligible again.

[16] See Eurostat government debt statistics `https://ec.europa.eu/eurostat/databrowser/view/gov_10q_ggdebt/default/table?lang=en`.

[17] In the fourth quarter of 2015 the German central sovereign debt was euro $1,372,200$ million while the German general government debt including regional and local debt was euro $2,178,095$ million. See also `https://www.ecb.europa.eu/press/pressconf/2015/html/is151203.en.html`.

[18] Deviations from the issuer limit could occur on a case-by-case basis.

2.2 Data

In this section we describe the datasets we use and how we combined them to compile an exhaustive database for our analysis.

Bond characteristics (time-to-maturity) and daily prices (yields) data for sovereign bonds are obtained from Bloomberg. For the prices we use Bloomberg Generic quotes that are a single-security composite derived from electronic dealer contribution. We complement the price and volume data using Trax market data that provides daily executed prices (low, mid and high) and bid-ask quotes at bond level, and monthly volumes. Trax is a global electronic bond trading platform that processes approximately 65% of all fixed income transactions in Europe.[19]

For bond data characteristics we use the ECB's Centralized Security Database (CSDB) that contains information on all active debt securities issued in the euro area providing static information on each single bond as country, coupon-type (fixed, floating, and zero), outstanding amount, maturity date and issuer (as central government, state or region government, local government etc..).

We merge this data with information on executed trades for the PSPP. Purchases are observed at bond level and daily frequency. We observe the amount purchased and the executed price and whether the trade is executed by the ECB or an NCB. In addition, we know the counter-party identity.

Finally, we use special repo rates data from the Brokertec repo platform that covers a significant share of the German sovereign repo market transactions.[20] The dataset consists of intraday transactions but we obtain daily observations computing a weighted average of the special repo rate during the day for each bond and repo maturity j using the transacted volume as a weight.[21]

[19] Trax constitutes the closest equivalent to FINRA's public trade tape in the US - Trade Reporting and Compliance Engine (TRACE). See page 5 of BlackRock's report `https://www.blackrock.com/corporate/literature/whitepaper/viewpoint-addressing-market-liquidity-euro-corporate-bond-market-2016.pdf`.

[20] There are two types of repo transactions: special repos and general collateral repos. In special repos, the party delivering the security must deliver a specific asset (with a specific ISIN code), while in general collateral repos (GC repos) he/she can choose among a basket of possible assets. Special repos imply the payment of a special rate. The special rate can be lower than the general repo rate, reflecting the convenience yield of the asset - how much sought-after the asset is.

[21] We have tick-by-tick transaction-level information, including the type of repo contract, general collateral (GC) or special, the ISIN of the underlying government bond, the repo interest rate paid on each transaction, and the volume of the transaction. We consider three main repo maturities: i) overnight (ON), when the repo settles on the trade date T and the bond is repurchased the next business day $T + 1$; ii) tomorrow next (TN), when the repo settles at the trade date plus one business day $T + 1$ and the bond is repurchased the following business day $T + 2$; and iii) spot next (SN), when the repo settles at $T + 2$ and the bond is repurchased at $T + 3$.

Panel A of Table 1 provides the characteristics of the outstanding universe of German sovereign bonds over our sample period (March 9, 2015 - February 27, 2017).[22] We report the mean and standard deviation computed at the bond-day level. We observe that the average maturity is 6.45 years with an average yield of 0.1%. The share of fixed-rate coupon bonds is approximately 93%.[23] The share of bonds issued by the German central government is approximately 84%. A small fraction of the bonds is used in the repo market as collateral and the large majority of these bonds is issued by the German central government. The average special repo rate is -0.48%.

Table 1. Summary statistics

	Obs.	Mean	St. dev
Panel A - Outstanding universe			
Time-to-maturity (years)	90,725	6.45	4.30
Coupon rate (%)	90,725	1.27	1.47
Outstanding amount (euro millions)	90,725	3,630	6,530
Yield (%)	90,725	0.10	0.46
Share fixed rate coupon (%)	90,725	92.78	3.18
Share central govern. (%)	90,725	83.79	2.59
Special repo rate (%)	15,243	-0.48	0.24
Panel B - ECB & NCB			
Dum. Purchase	90,725	0.07	0.26
Time-to-maturity (years)	6,989	11.17	7.42
Coupon rate (%)	6,989	2.61	1.88
Outstanding amount (euro millions)	6,989	14,800	7,120
Dum. Fixed rate coupon	6,989	0.96	0.20
Dum. Central govern.	6,989	0.91	0.28
Special repo rate (%)	5,829	-0.46	0.26
Monthly cum. purchases central gov. / Outstanding (%)	1,478	0.96	1.46
Monthly cum. purchases central gov. / Trax volume (%)	1,430	8.61	18.25
Num. counterparties	6,989	1.29	0.58

Panel B provides a breakdown of the characteristics of the bonds purchased by the Eurosystem. The same bonds purchased via the PSPP program have on average a higher coupon (2.61%), a higher remaining maturity (11.17 years) and a larger outstanding amount (€$14,800$ million) compared to the bonds that were not purchased. The purchases mainly consist of bonds issued by the central government (91% of the overall purchases) although our sample also accounts for regional and local bonds that became eligible on December 3, 2015. The large majority of the purchases consist of bonds that are used as collateral in the repo market on the same date with an

[22]We consider only bonds for which we can observe a daily Bloomberg generic price (BGN).

[23]The share is computed using the nominal outstanding amount observed for each bond with a daily frequency.

average special repo rate of -0.46%.

To assess whether the Eurosystem purchases account for a large share of the trading activity, we first scale the monthly cumulative bond purchases with the corresponding outstanding amount. The Eurosystem on average buys almost 1% of the outstanding amount of German sovereign bonds within each month. Then, we scale the monthly cumulative bond purchases with monthly executed volume for the same bond by Trax. For the central government bonds, we observe that purchases account for 8.61% of the traded volume within each month, suggesting that the Eurosystem is a large player in the German sovereign bond market. Finally, the Eurosystem execute on average daily trades on the same bond with approximately one counterparty on average.

3 The price anomaly

We follow the approach of Lou, Yan, and Zhang (2013) to analyze the time-series pattern in bond yields around the end-of-month. For each bond, we use the yield from 9 trading days before to 10 trading days after the end-of-month and compare them with the yield on the beginning-of-window day. That is, we track the same bond throughout the $20-$day window around each end-of-month. Thus, for bond i we compute the time series of $Y_{i,j,t} - Y_{i,j,-9}$ where $Y_{i,j,t}$ is the yield of the bond i at day t of window j (from -9 to $+10$) and $Y_{i,j,10}$ is the yield of the same bond on the end-of-window day ($t = +10$). When we compute the window, we exclude public holidays.

The pattern in sovereign yields around the end-of-month can be seen in the top panel of Figure 3. We plot the time series average of $Y_{i,j,t} - Y_{i,j,-9}$ based on the regression

$$Y_{i,j,t} - Y_{i,j,-9} = \sum_{t=-9}^{T=10} \alpha_t \times \mathrm{D}_t + \epsilon_{i,j,t} \tag{1}$$

where D_t is a dummy variable that is equal to one on day t with t ranging from -9 to 10 (including $t = 0$), and $t = 0$ being the end-of-month day.

We observe a clear asymmetric pattern: German sovereign bond yields (prices) steadily decrease (increase) relative to the beginning of the window on average by 2.46bps before end-of-month dates and rise (drop) by 1.76bps shortly thereafter.[24] Our estimates are of similar magnitude as the effects documented by Lou, Yan, and Zhang (2013) even though the average level of yields of 0.1%

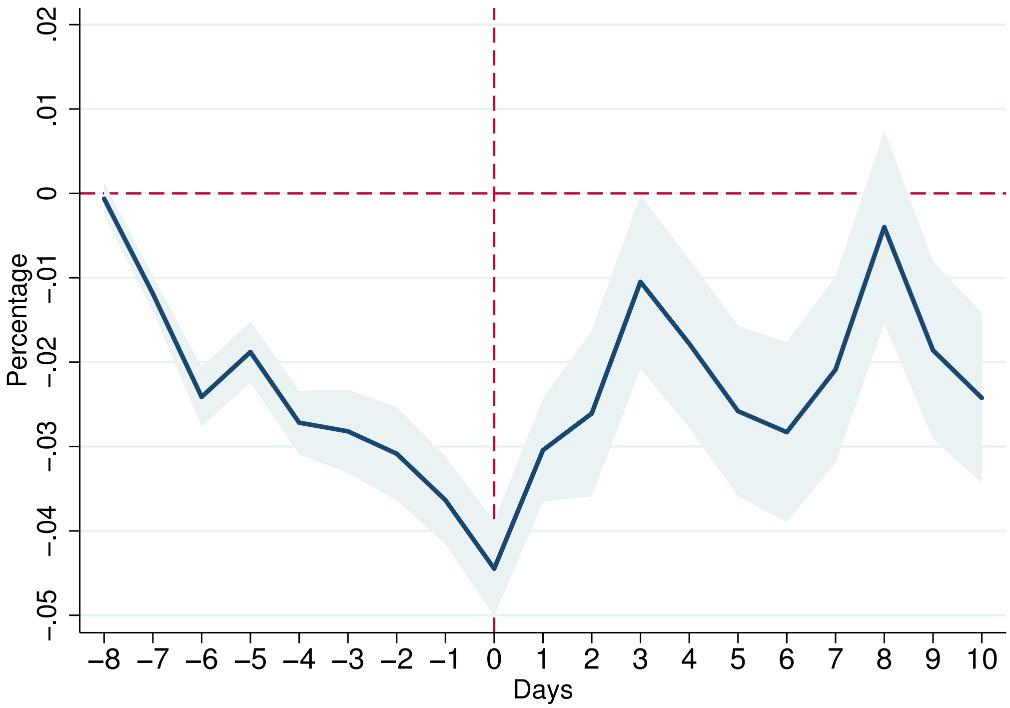
[24] We also exclude the end-of-year windows and end of quarters for robustness.

is much lower in our sample.

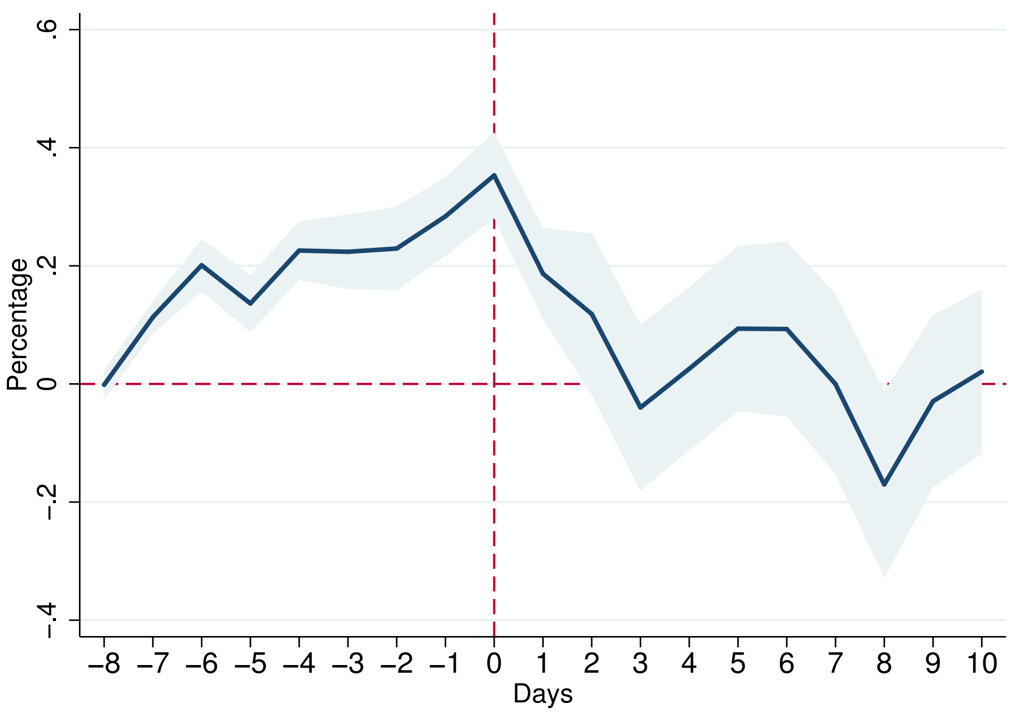
They document a reverse V-shaped pattern of bond yields: US Treasury security yields in the secondary market increase significantly in the few days before Treasury auctions and decrease thereafter. In particular, they find that the US Treasury yield of $2-$year notes increases on average by 2.53 bps during the five-day period before the auction and decreases by 2.32 bps during the five-day period after the auction. However, the average yield in their sample from January 1980 to June 2008 ranges from 6.36% ($2-$year notes) to 7.57% ($10-$year notes).

In the bottom panel of Figure 3, we redo the analysis using holding returns $\log(P_{i,j,t}/P_{i,j,-9})$ where $P_{i,j,t}$ is the price of the bond i at day t of window j (from -9 to 10) and $P_{i,j,-9}$ is the price of the same bond on the start-of-window day ($t = -9$). For bond log-returns we observe a reverse asymmetric pattern: the cumulative price change is largest at the end of a month and declines thereafter.

Table 2 and Figure 4 and 5 address some potential concerns. First, we re-estimate our regression specification controlling for bond times window fixed effects (Column (1) and (3)). This is a non-parametric way to control for window-level variation accounting for changes in bond market conditions at bond level. Standard errors are clustered at bond times window level. We find that all coefficients are almost unchanged relative to Figure 3 and the coefficients on the dummy D_t for days ranging from -9 to 0 remain statistically significant at the 1% level.



(a) Yield Changes



(b) Log Returns

Figure 3. Yields and holding returns around end-of-month. The figure plots the coefficients α_t from the OLS regression. In panel (a) the dependent variable is $Y_t - Y_{-9}$, where Y_t is the yield on day t. In panel (b) the dependent variable is $\log(P_t/P_{-9})$, where P_t is the price of the bond i at day t. The bond yields and prices are from Bloomberg. t ranges from -9 to 10 (including $t = 0$) and $t = 0$ is the last day of the month. The main independent variable is daily indicator variables. The sample period is from March 9, 2015 to February 27, 2017. Shadow area is 95%-confidence interval.

Table 2. Bond holding returns and yields around the end-of-month - This table reports the coefficients of the regression where the dependent variable is i) the bond holding return $\log(P_{i,j,t}/P_{i,j,-9})$; and ii) the bond yield $Y_{i,j,t} - Y_{i,j,-9}$, where $P_{i,j,t}$ ($Y_{i,j,t}$) is the price (yield) of the bond i at day t of window j (from -9 to 10) and $P_{i,j,-9}$ ($Y_{i,j,-9}$) is the price (yield) of the same bond on the end-of-window day ($t = -9$). The independent variable is day t, with t ranging from -9 to 10 (including $t = 0$), and $t = 0$ being the end-of-month day. The regression includes bond-window fixed effects (Columns (1) $-$ (9) and (11) $-$ (12)) and pair-window fixed effects (Column (10)). Standard errors are clustered at bond-window level and pair-window level. Standard errors are reported in parentheses. $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Return		Yield		Return	Yield	Return	Return	Return	Spread	Placebo - Yield	
	All	Without quarters	All	Without quarters	ECB executed	ECB executed	TraX traded	repo adjusted	without newly issued bonds	state vs reg. pairs	Without quarters	Only quarters
- 8	-0.001	-0.065***	-0.001	0.006***	0.076*	-0.008***	0.048***	-0.000	-0.002	-0.001	0.024***	-0.016
- 7	0.113***	0.084***	-0.012***	-0.009***	0.066	-0.011***	0.080***	0.116***	0.112***	-0.008***	0.030***	-0.025***
- 6	0.201***	0.181***	-0.024***	-0.022***	0.197***	-0.018***	0.166***	0.205***	0.197***	-0.009***	0.031***	0.009
- 5	0.136***	0.132***	-0.019***	-0.018***	0.184**	-0.019***	0.133***	0.141***	0.131***	-0.009***	0.026***	0.020
- 4	0.226***	0.127***	-0.027***	-0.017***	0.280***	-0.030***	0.274***	0.232***	0.224***	-0.011***	0.030***	0.009
- 3	0.224***	0.110***	-0.028***	-0.016***	0.423***	-0.044***	0.241***	0.232***	0.224***	-0.012***	0.025***	0.003
- 2	0.229***	0.124***	-0.031***	-0.020***	0.503***	-0.053***	0.275***	0.238***	0.228***	-0.012***	0.002	-0.031
- 1	0.284***	0.138***	-0.036***	-0.021***	0.518***	-0.060***	0.314***	0.294***	0.281***	-0.016***	-0.007	-0.050**
0	0.353***	0.211***	-0.044***	-0.029***	0.533***	-0.060***	0.332***	0.365***	0.350***	-0.017***	-0.011*	-0.051**
1	0.187***	0.023	-0.030***	-0.012***	0.322***	-0.048***	0.188***	0.199***	0.183***	-0.015***	-0.010	-0.046**
2	0.118	-0.052	-0.026***	-0.007	0.214**	-0.038***	0.163***	0.133	0.113	-0.008**	-0.011	-0.042**
3	-0.040	-0.254**	-0.010	0.013*	0.126	-0.024***	0.095**	-0.025	-0.047	0.002	0.006	-0.061***
4	0.025	-0.166	-0.018***	0.003	0.167*	-0.034***	-0.009	0.042	0.018	0.002	0.019**	-0.065***
5	0.093	-0.126	-0.026***	-0.002	0.085	-0.021***	0.070	0.111	0.086	-0.003	0.005	-0.073***
6	0.092	-0.116	-0.028***	-0.007	0.104	-0.024***	0.108*	0.112	0.083	-0.000	0.015**	-0.068***
7	-0.001	-0.194	-0.021***	-0.001	-0.022	-0.016	0.069	0.020	-0.010	-0.001	0.021***	-0.074***
8	-0.171*	-0.275**	-0.004	0.007	-0.214	0.005	-0.143**	-0.149	-0.182*	0.002	0.023***	-0.037**
9	-0.070	-0.192	-0.015**	-0.002	-0.050	-0.004	-0.138*	-0.047	-0.081	-0.003	0.018**	-0.047***
10	-0.020	-0.128	-0.021***	-0.009	0.203	-0.034***	-0.016	0.005	-0.029	-0.009**	0.012	-0.076***
Obs.	14,694	11,431	14,694	11,431	3,818	3,818	14,252	14,694	14,528	5,164	5,400	1,260
R^2	0.4758	0.4569	0.4912	0.4717	0.5017	0.4516	0.5019	0.4755	0.4751	0.7345	0.6846	0.7517
Bond - Wind. FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	Yes	Yes
Pair - Wind. FE	-	-	-	-	-	-	-	-		Yes	-	-

Second, we repeat our analysis excluding the end-of-quarter windows (Column (2) and (4)). Recent empirical literature documents that the introduction of the Basel III leverage ratio regulation impacts bond markets at quarter-ends due to "window-dressing" effects (Munyan (2017)). We find that the results are qualitatively similar to the ones reported for the full sample (Column (1) and (3)). The coefficients associated with yield differential are at least a third smaller than the corresponding coefficients in specifications with quarter-end windows but all results remain statistically significant at the 1% level over the nine days period before the end-of-month. Our estimates indicate that German bond prices increase more at the end-of-quarters. Extant literature has argued that dealers' activity in the bond market falls significantly around quarter end, as the cost of expanding their balance sheet increases (Arrata et al. (2020), Corradin et al. (2020) and Breckenfelder and Ivashina (2021)).[25] It appears this has a reinforcing effect on the pattern we identify. In the context of the model we present below, this can be explained by a reduction in competition among dealers to provide an executable quote around quarter end.[26]

Third, the documented price pattern around the end-of-month is not unique to Bloomberg quotes. Figure 4 shows a very similar pattern when we use the Eurosystem executed prices. Sovereign bond yields steadily decrease relative to the start of the window on average by 3bps (2.46bps) before end-of-month dates. The magnitudes are larger than the previous ones (Column (5) and (6)) but the sample is smaller and different, as we restrict the sample to bonds with nonzero Eurosystem purchases. When we also re-estimate our main specification using Trax traded prices to compute the holding return (Column (7)), we find that all coefficients are almost unchanged relative to Column (1) and remain statistically significant at the 1% level when we look at the nine days period before the end-of-month. As shown in Figure 4, when we estimate the main specification using Bloomberg quotes and Trax traded prices on the nonzero Eurosystem purchases sample, we find no visible differences. Overall, Bloomberg quoted, Trax traded and Eurosystem executed prices are aligned. Our results are consistent with Schlepper et al. (2020) who investigate

[25]This recent literature documents that the Basel III leverage ratio regulation affects repo market activities. The leverage ratio is a non-risk weighted measure that requires banks to hold capital in proportion to the overall size of their balance sheet. Repos expand a bank's balance sheet and therefore attract a capital charge under the leverage ratio. As the margin on repos is low a binding leverage ratio makes it more costly for banks to engage in repo compared to engaging in activities with higher margins (but equal capital charge), providing them with an incentive to reduce their activity (see also Duffie and Krishnamurthy (2016) and Duffie (2018)).

[26]This could also be related to the fact that repo rates increase around quarter end making it more costly for dealers to sell a bond if they don't already have it in inventory.

the price impact of the PSPP on German sovereign bonds using minute-by-minute frequency MTS data. They document that transacting dealers quickly update bond quotes in the MTS market and the remaining dealers quickly follow suit.

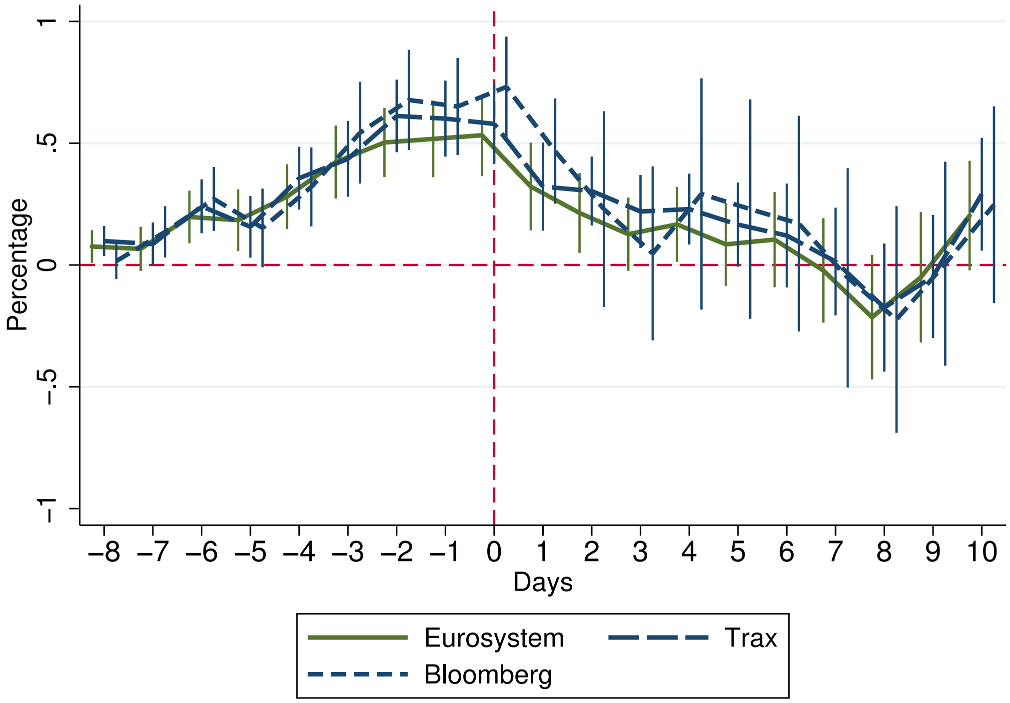
Fourth, another potential concern with our return or yield pattern is the variation in repo funding costs around the end-of-month. To address this issue, we repeat our analysis in Column (8) of Table 2, but now we adjust for repo funding costs when computing holding returns. Specifically, we subtract the cumulative special repo rates for the same bond scaled by 1/360 from the bond holding return.[27] Our main results are unaffected by this adjustment.

Fifth, one potential concern is that the pattern we uncover is affected by issuance activity. If new bonds are issued at the end-of-month, then issuance may create some upward price on newly issued bonds driving our results. To address this issue we repeat our analysis in Column (9) excluding newly issued bonds from our sample. We find that all coefficients are almost unchanged relative to Column (1).

Sixth, one critique with our yield and holding return pattern is the time variation (or trend) of yields (or prices) around the end-of-month within the window. To address this issue, we compute a yield basis free from credit risk by comparing direct yields on German central government debt and direct yields on German sovereign debt issued by a German region (i.e. Bavaria) for similar maturity in years and coupon rate. The latter securities became eligible for PSPP purchases after the start of the programme. For each pair, we use the yield basis during both the 9 trading days before and 10 trading days after the end-of-month and compare them with the yield basis on the beginning-of-window day. Then, we estimate our regression specification restricting the sample to the ineligibility period of the German regional bonds and controlling for pair fixed effects and window fixed effects respectively (Column (10)).[28] Figure 5 shows the point estimates. As shown, the asymmetric pattern previously documented is by and large unchanged, despite the shorter sample period due to the ineligibility of the German regional bonds at the beginning of our sample. After the end-of-month, we find no visible differences in the yield basis.

[27] We use the spot next special repo rates.

[28] Standard errors are clustered at both pair and window level.



(a) Yield Change

Figure 4. Holding returns based on Eurosystem executed prices around end-of-month. The figure plots the coefficients α_t from an OLS regression. The dependent variable is $\log(P_t/P_{-9})$, where P_t is the price of the bond i at day t. t ranges from -9 to 10 (including $t = 0$) and $t = 0$ is the last day of the month. The main independent variable is daily indicator variables. The continuous line indicates the point estimates when the bond prices are based on Eurosystem executed prices. The long-dashed line indicates the point estimates when the bond prices are based on Trax traded prices. The dashed line indicates the point estimates when the bond prices are based on Bloomberg BGN quotes. The spike is confidence intervals at 95%.

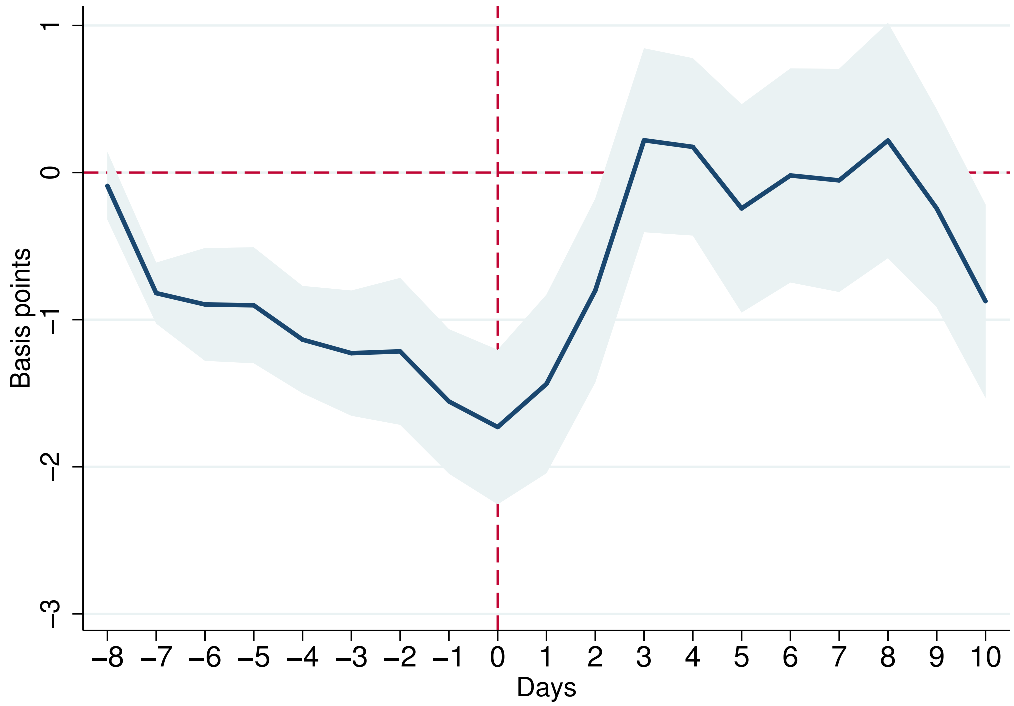


Figure 5. Yield basis around end-of-month. The figure plots the coefficients α_t from an OLS regression. The dependent variable is $YB_t - YB_{-9}$, where YB_t is the yield basis on day t computed as the difference between the yield of a German central government bond and the yield of a German sovereign bond issued by a German region with similar maturity in years and coupon rate. t ranges from -9 to 10 (including $t = 0$) and $t = 0$ is the last day of the month. The main independent variable is daily indicator variables. Shadow area is confidence intervals at 95%.

Finally, to provide first evidence that the price anomaly might be linked to the PSPP, we run our analysis when the quantitative program has not started. In particular, we focus on the period October 15, 2012 - April 15, 2014.[29] The beginning of our sample is after the announcement of the Outright Monetary Transactions (OMT) programme that had a significant impact on euro area government bond yields and ends the euro area sovereign debt crisis.[30] We end our sample on April 15, 2014 before ECB President Draghi used a speech in Amsterdam on 24 April 2014 to communicate that ECB could have engaged in a large-scale asset purchase programme to directly influence longer-term yields due to the prolonged period of low inflation in the euro area (Draghi (2014), Rostagno et al. (2021)).

[29] We choose mid-of-month dates given the 20−day window around each end-of-month empirical design.

[30] The OMT was announced on 2 August 2012 and the the technical framework of these operations was formulated on 6 September 2012. The program can be used to purchase unlimited amounts of government bonds of member states subject to a European Stability Mechanism (ESM) programme.

Table 2 reports the estimates of the price pattern across all windows excluding end-of-quarters (Column (11)) and on end-of-quarters windows (Column (12)). We observe that German sovereign bond yields (prices) do not steadily decrease (increase) relative to the beginning of the window and rise (drop) shortly thereafter. When we exclude end-of-quarter windows we observe that prices on average do not move in the first days of the window, they decrease three days before the end-of-month and start to recover two days after the end-of-month. However, the estimates around the end-of-month are almost statistically insignificant. Column (12) shows a clear downtrend in yields when we estimate our coefficients on end-of-quarter windows while our empirical estimates provide a more pronounced asymmetric price pattern when the PSPP is active.

In the Appendix, we provide further robustness analysis (see Table A-I). First, we run the analysis on the yield spread as the bond yield minus the interest swap rate of the same time-to-maturity (Column (1)). Second, we exclude bonds that are subject to the blackout period (Column (2) and (3)) (Arrata et al. (2020), De Santis and Holm-Hadulla (2020)). During this period the Eurosystem does not buy bonds around the issuance or re-issuance dates. It also refrains from buying bonds of similar residual maturity.[31] Third, we exclude bonds entering the Bloomberg Germany Treasury Bond Index.[32] This addresses the potential concern that the pattern can be attributed to temporary spikes in investor demand for specific securities due to the index rebalancing. Finally, we exclude the bonds that are ineligible for Eurosystem purchases according to the ECB deposit rate rule.[33] Overall, we find that the results reported in Table A-I are qualitatively similar to the ones reported in Table 2.

4 The model

We propose a simple search-bargaining model of the Eurosystem purchases to explain qualitatively the price pattern observed in the data. We first assume the central bank wants to purchase 1 unit of bond from N dealers (we consider multiple units below). We assume each dealer will be contacted and quote a bond price with probability $\eta < 1$. This can be justified by (i) a cost of searching too

[31] This rule intends to avoid any monetary financing of the government.

[32] This index is used as a benchmark index for Bund ETFs as the iShares Germany Government Bond ETF.

[33] The yield of eligible bonds had to be above the ECB deposit facility rate, which was equal to 20bps at the launch of the programme. On January 19, 2017, the ECB governing council decided to relax this rule allowing further purchases of bonds with a yield below the deposit facility rate.

many dealers, (ii) an operational cost for dealers to always be present in the market at all time to respond to an inquiry, (iii) the potential lack of inventory in the specific bond at a particular dealer when contacted by the bank perhaps because it was just sold to another client, or a combination of these. We note that it is straightforward to let η depend on the round of trading.[34]

We assume that there are T rounds of trading for the bank to buy from the dealers and that the maximum value the bank is willing to pay for one unit in the final round is v. The cost to the dealers is assumed to be 0.[35] So v is the 'excess' premium the bank is willing to pay over and above the 'fair price' to fill its mandate of acquiring 1 bond in the market. We assume dealers and bank try to maximize the expected gains from trading.

We assume symmetric strategies equilibrium for all dealers who are ex-ante identical. We consider an equilibrium where dealers follow mixed strategies and quote according to a continuous density with cumulative distribution function $H_t(p)$ in round t. The equilibrium price quote density can be derived recursively. Let's start in the last period $t = T$. Conditional on quoting a price, a dealer will be indifferent between any p, drawn from $H_T(p)$ defined on $[\underline{p}_T, \overline{p}_T]$, if and only if she gets the same expected gain at every price. The maximum price the bank is willing to accept in the last period is v, therefore $\overline{p}_T = v$. If the dealer quotes v her expected profit is $(1-\eta)^{N-1}v$, that is she earns v only if she is the only dealer to quote a price in that period (which happens with probability $(1-\eta)^{N-1}$), because if any other dealer is contacted, since dealers quote from a continuous density, with probability 1 there will be a lower price available in the market, which will be preferred by the bank. Now, if the dealer quotes another price $p \in [\underline{p}_T, v)$ then her expected profit is $p \sum_{k=0}^{N-1} C_{N-1}^k \eta^k (1-\eta)^{N-1-k} (1-H_T(p))^k$. That is she gets p only if the k other dealers, that are present with probability $C_{N-1}^k \eta^k (1-\eta)^{N-1-k}$, quote a price that is greater than p, which occurs with probability $(1-H_T(p))^k$.[36]

The indifference condition then allows to deduct the equilibrium density. For all $p \in [\underline{p}_T, \overline{p}_T]$ we have:

[34] Alternatively, we can think of η as the exogenous probability with which the bank chooses to contact a given dealer. Why would the bank not contact all dealers in every round? Perhaps because it considers that process too costly. Note that in the implementation of the PSPP, as described in section 2.1, the Eurosystem requires a minimum of 3 quotes from 3 different dealers. One might think this could be sufficient for Bertrand competition to kick in. However, in reality, it is plausible that some of the contacted dealers give relatively wide quotes if they do not have the asset in inventory and anticipate a costly reverse repo transaction to obtain the asset. An interesting extension for future research would be to endogenize the choice of η by dealers.

[35] It is straightforward to extend to any fixed cost $c < v$ by simply redefining v.

[36] We use the standard notation for the binomial coefficient $C_n^k = \frac{n!}{k!(n-k)!}$.

$$p\sum_{k=0}^{N-1} C_{N-1}^{k}\eta^{k}(1-\eta)^{N-1-k}(1-H_T(p))^{k} = v(1-\eta)^{N-1} \tag{2}$$

The lower bound $\underline{p}_T$ is the lowest value such that $H_T(\underline{p}) = 0$.

Now, we can derive the equilibrium quoting density in every round recursively. To that effect, suppose that we have $H_{t+1}(p) : [\underline{p}_{t+1}, \overline{p}_{t+1}] \to [0,1]$ the density with which dealers quote in round $t+1$. Then consider the optimal quoting behavior of a dealer at date t. Again she will quote optimally from a continuous density $H_t(p)$ so as to get the same expected gain for every quoted price in equilibrium. Similarly to what happens at date T, we have the following indifference condition which determines the density for any price $p \in [\underline{p}_t, \overline{p}_t]$:

$$p\sum_{k=0}^{N-1} C_{N-1}^{k}\eta^{k}(1-\eta)^{N-1-k}(1-H_t(p))^{k} = \overline{p}_t(1-\eta)^{N-1} \tag{3}$$

We can use Euler's binomial formula to simplify this equation to:

$$p\,(1-\eta H_t(p))^{N-1} = \overline{p}_t(1-\eta)^{N-1}$$

It follows that $\forall t$ the quoting density is:

$$H_t(p) = \frac{1}{\eta} + (1-\frac{1}{\eta})\left(\frac{\overline{p}_t}{p}\right)^{\frac{1}{N-1}} \tag{4}$$

The lower integration bound is found by solving $H_t(\underline{p}_t) = 0$:

$$\underline{p}_t = \overline{p}_t(1-\eta)^{N-1} \tag{5}$$

This has a nice interpretation: if a dealer quotes the lowest price, she will sell with probability one, and in expectation earn the same expected revenue as when she quotes the highest price, in which case she sells if she is the only one making a market (with probability $(1-\eta)^{N-1}$).

Thus we can compute the average price quoted by dealers (conditional on quoting) in every round:

$$p_t^a = \int_{\underline{p}_t}^{\overline{p}_t} p\, dH_t(p) = [pH_t(p)]_{\underline{p}_t}^{\overline{p}_t} - \int_{\underline{p}_t}^{\overline{p}_t} H_t(p)\, dp \tag{6}$$

$$= \overline{p}_t \gamma_N \tag{7}$$

$$\gamma_N = \begin{cases} \frac{(1-\eta)(1-(1-\eta)^{N-2})}{\eta(N-2)} & \text{if} \quad N > 2 \\ (1 - \frac{1}{\eta}) \log(1-\eta) & \text{if} \quad N = 2 \end{cases} \tag{8}$$

Similarly, we can compute various moments of the quoted price distribution.

It remains to identify the upper integration bound $\overline{p}_t$. What is the highest price the bank will be willing to accept in round t? It should be the highest price at which the bank becomes indifferent between trading now or continuing to the next round. We define the upper reservation price recursively by noting that in the last trading round $\overline{p}_T = v$ (which gives a trading surplus of $s = v - \overline{p}_T = 0$). At $T-1$, the upper reservation price will be such that $v - \overline{p}_{T-1} = \beta\{\mathbb{E}[\hat{s}_T]\}$, where we define the maximum surplus that the bank can obtain if she trades in round t by

$$\hat{s}_t = \max[s_t^1, \ldots, s_t^N], \tag{9}$$

and where we define the surplus from transacting with dealer i by $s_t^i = v - p_t^i$ if dealer i quotes a price in round t and $s_t^i = 0$ otherwise. We also allow for a discount factor $\beta \in [0, 1]$ to reflect the bank's impatience or rate of time preference.[37]

Similarly, in every round $t < T$ we obtain the upper reservation price recursively by solving:

$$v - \overline{p}_t = \beta\{\mathbb{E}[\hat{s}_{t+1} + \mathbf{1}_{\hat{s}_{t+1}=0}(v - \overline{p}_{t+1})]\tag{10}$$

[37]Note that we implicitly assume that the bank always buys at the lowest price quoted to her in any round. Actually, this is also the optimal strategy for the bank, since given the definition of the upper reservation price, it is never optimal to wait to buy later. So in the case where the bank seeks to buy only 1 asset, she would actually purchase the asset the first time a dealer quotes an 'executable' quote to her. Since the probability of a trade in a given round is $p^{trade} = 1 - (1-\eta)^N$, then on average the first trade would be expected to occur at time $\tau = 1/p^{trade}$.

It remains to derive the distribution of $\hat{s}_t$. To that effect we note that for any $v - p > 0$:

$$\begin{aligned}
\hat{H}(v-p) := Prob(\hat{s} \leq v-p) &= Prob(s^1 \leq v-p, \ldots, s^N \leq v-p) && (11)\\
&= (1-\eta+\eta(1-H(p)))^N && (12)\\
&= (1-\eta H(p))^N && (13)\\
&= (1-\eta)^N (\frac{\overline{p}}{p})^{\frac{N}{N-1}} && (14)
\end{aligned}$$

We can then compute the expected surplus:

$$\begin{aligned}
\mathbb{E}[\hat{s}] &= -\int_{\underline{p}}^{\overline{p}} (v-p) d\hat{H}(v-p) && (15)\\
&= -[(v-p)(1-\eta H(p))^N]_{\underline{p}}^{\overline{p}} - \int_{\underline{p}}^{\overline{p}} (1-\eta H(p))^N \, dp && (16)\\
&= v - \underline{p} - (v-\overline{p})(1-\eta)^N - (1-\eta)^N \int_{\underline{p}}^{\overline{p}} (\frac{\overline{p}}{p})^{\frac{N}{N-1}} \, dp && (17)\\
&= v(1-(1-\eta)^N) - \overline{p} N\eta(1-\eta)^{N-1} && (18)\\
& && (19)
\end{aligned}$$

We have now characterized the problem and obtained a recursive solution. Let's summarize our results on the equilibrium price quote density in any round t: $H_t(p) : [\underline{p}_t, \overline{p}_t] \to [0,1]$:

$$\begin{aligned}
H_t(p) &= \frac{1}{\eta} - \frac{(1-\eta)}{\eta}(\frac{\overline{p}_t}{p})^{\frac{1}{N-1}} && (20)\\
\underline{p}_t &= \overline{p}_t(1-\eta)^{N-1} && (21)\\
\overline{p}_T &= v && (22)\\
v - \overline{p}_t &= \beta \left\{ v - \overline{p}_{t+1}(1-\eta)^{N-1}(1+(N-1)\eta) \right\} \quad \forall t < T && (23)\\
\mathbb{E}[\hat{s}_t] &= v(1-(1-\eta)^N) - \overline{p}_t N\eta(1-\eta)^{N-1} && (24)
\end{aligned}$$

Note that if there is no discounting ($\beta = 1$) then the recursion for the upper reservation price simplifies to:

$$\overline{p}_t = (1-\eta)^{N-1}(1+(N-1)\eta)\overline{p}_{t+1} \tag{25}$$

$$= (1+(N-1)\eta)\underline{p}_{t+1} \quad \forall t < T \tag{26}$$

Clearly, in that case, the trading range increases at a geometric rate at each trading round. Thus, the average price at which we expect the transaction to occur increases towards maturity. As we approach maturity, dealers recognize that they have more bargaining power (as they are less likely to face competition from dealers in future rounds) and thus quote higher prices. This intuition holds for the more general case with $\beta < 1$, as we illustrate in figure 6 below. The earlier the bank can trade the higher the expected surplus. The expected surplus of the bank drops towards maturity, and the drop is more severe the less competition dealers face, that is the smaller is $N\eta$, and the more impatient the bank is, that is the lower is β.

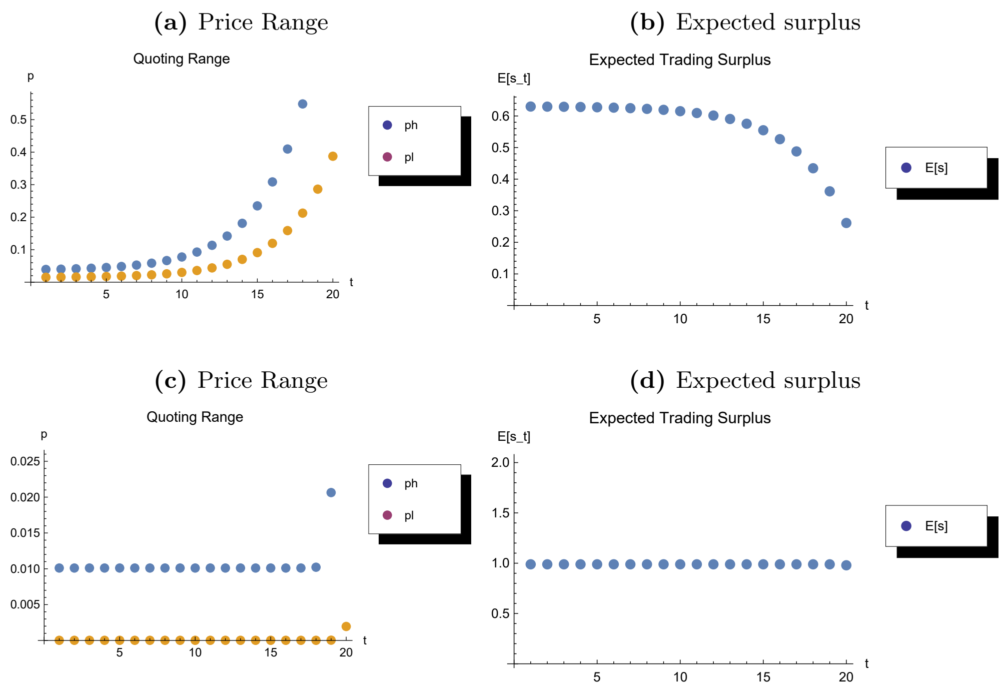
As we show in panel (c) and (d), if the degree of competition among dealers is very high (here $\eta = 0.5$, which implies that on average 5 dealers quote a price in every round), then the trading range is approximately constant over the trading horizon and concentrated close to zero (except for the last trading round where the upper end of the range is by definition $\overline{p}_T = v \equiv 1$). With high competition, the bank earns all the surplus and we can see in panel (d) that the expected surplus of the bank's trade is approximately constant and equal to 1. That is, with high competition the bank expects to pay a price close to 0 in every trading round and to extract the full surplus. Instead, with low competition as illustrated in panel (a) and (b) then the trading price is expected to increase significantly as we approach maturity and the bank's expected surplus of a trade decreases severely the closer to maturity she trades.

The figure above characterizes the expected trading price when the bank seeks to buy one unit over multiple rounds. In practice the bank seeks to purchase several units. We turn to that case next.

4.1 Purchasing Multiple Units in one round

We now consider the case where the bank wants to buy several units, e.g., $U \geq 1$ by contacting N dealers who each can sell only one unit when contacted. As before we assume that dealers quote a

Figure 6. Model illustration Panel (a) shows the lower and upper prices of the quoting range $[\underline{p}_t, \overline{p}_t]$. Panel (b) shows the unconditional expected trading surplus $E[\hat{s}_t]$ obtained from trading in various rounds as a function of time $t \in [0, T = 20]$ for a value of $\eta = 0.1$, $\beta = 0.99$, $N = 10$, and $v = 1$. Panels (c) and (d) show the quoting range and expected trading surplus for a higher $\eta = 0.5$, which implies a high degree of competition among dealers in every round.



(a) Price Range

(b) Expected surplus

(c) Price Range

(d) Expected surplus

price for that unit with probability η.

Consider first the final trading round. Clearly, if the number of units that the bank still wants to purchase is $U > N$, then every contacted dealer knows that she is not in competition with any other dealer and thus will quote a price of $p_T = v$, the reservation price of the bank. Instead, if $U < N$, then dealers will quote from a continuous distribution $H(p) : [\underline{p}, \overline{p}] \to [0, 1]$, so as to be indifferent between every price. The maximum price $\overline{p} = v$ will be received only if there are at most $U - 1$ dealers who quote a price among the remaining $N - 1$ dealers. Instead, if the dealer quotes a price $p < v$, then the bank will buy at that price if among all other dealers, who quote a price, at most $U - 1$ quote a lower price. It is helpful to define $\hat{s}^i_N$ to be the i^{th} largest order statistic among a set of N i.i.d. random variables $s^1, \ldots, s^N$, where the $s^i = (v - p^i)\psi^i$ where the p^i are drawn from the distribution $H(p)$ and the ψ^i are binomial equal to 1 with probability η and 0 else. With this notation we can define the indifference condition in the final round as follows:

$$v\, Prob(\hat{s}^U_{N-1} \leq 0) = p\, Prob(\hat{s}^U_{N-1} \leq v - p) \tag{27}$$

Note that by definition of the order statistic (the u-highest r.v. in a set of n iid r.v. is smaller than α iff at most $u - 1$ r.v. selected in the set are higher than α), we have

$$Prob(\hat{s}^u_n \leq v - p) = \sum_{k=0}^{u-1} C^k_n (\eta\, H(p))^k (1 - \eta\, H(p))^{n-k} \tag{28}$$

It follows that the indifference condition can be rewritten as:

$$v \sum_{k=0}^{U-1} C^k_{N-1} \eta^k (1 - \eta)^{N-1-k} = p \sum_{k=0}^{U-1} C^k_{N-1} (\eta\, H(p))^k (1 - \eta\, H(p))^{N-1-k} \tag{29}$$

This equation can be solved for the equilibrium quoting density $H_{T,U}(p)$. We see that the indifference condition reduces to the one unit solution derived in the previous round when $U = 1$ (i.e., when the bank has only one remaining unit to buy in the final round). Since we were not able to get an explicit solution for $H(p)$ we solve this equation numerically.

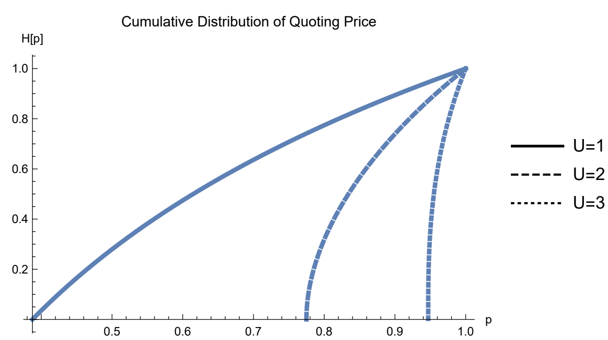
Finally, the lowest quoting price $\underline{p}$ can be found by solving for $H(\underline{p}) = 0$. Note that the equation above then implies the value for $\underline{p}$ satisfies:

$$\underline{p}_{T,U} = v \sum_{k=0}^{U-1} C_{N-1}^{k} \eta^{k} (1-\eta)^{N-1-k} \tag{30}$$

which states that the expected profit obtained by quoting the lowest value and getting a trade with probability 1 is equal to the expected profit of quoting the highest possible value and getting exercised only if no one else is quoting.

Figure 7 below shows the cumulative distribution function $H_{T,U}(p)$ in the final round T, when there are U units remaining to be purchased, for various values of $U \in \{1,2,3\}$. We see that as there are more units to be purchased the distribution function shifts to the right, that is $H_{T,1}(p) \geq H_{T,2}(p) \geq H_{T,3}(p)$, which reflects the fact that, all else equal, dealers have an incentive to quote higher prices in the final round, the more units the bank has to purchase to achieve its target. In turn, the bank's incentive is to buy in previous rounds to reduce the dealers' market power in the last round. We solve for the banks optimal bidding strategy in previous rounds next.

Figure 7. Quoting distribution in the final round $H_{T,U}(p)$ when bank still needs to purchase U units from N dealers, for $\eta = 0.3$, $N = 10$, and $v = 1$.



4.2 Purchasing multiple units over several trading rounds

Now we consider the case where the bank can spread the purchase of the U bonds across several T trading rounds. For simplicity we assume the bank can buy at most one unit per round in every round except the last round T, where she can buy as many units required to fill her objective.[38]

[38] It could be interesting to consider richer strategies where the bank can buy possibly multiple units from one bank or buy one unit from several banks in each round, depending on the various quotes obtained. We leave this for future research. Note that the present simplifying assumption is consistent with the implementation strategy of PSPP by

We further assume that in each round it is common-knowledge among the dealers how many units the Bank has bought, and therefore how many remain to be purchased. We define $H_{t,u}(p)$ the equilibrium quoting density for dealers in round t when the Bank has a total remaining objective of u units to buy (she therefore bought $U - u$ units in rounds prior to t). Since in round t the bank is contacting dealers to buy one unit, the quoting density satisfies the following indifference condition (similar to the one unit case studied before hand):

$$\overline{p}_{t,u}(1-\eta)^{N-1} = p \sum_{k=0}^{N-1} C_{N-1}^{k} \eta^{k} (1-\eta)^{N-1-k} (1 - H_{t,u}(p))^{k} \tag{31}$$

$$= p(1 - \eta H_{t,u}(p))^{N-1} \tag{32}$$

from which we obtain the density. Further, the minimum price a dealer will be willing to quote will satisfy:

$$\underline{p}_{t,u} = \overline{p}_{t,u}(1-\eta)^{N-1} \tag{33}$$

Together we obtain the explicit solution as in equation 4

$$H_{t,u}(p) = \frac{1}{\eta} - \frac{(1-\eta)}{\eta} (\frac{\overline{p}_{t,u}}{p})^{\frac{1}{N-1}} \tag{34}$$

It remains to compute the maximum price the bank will be willing to pay in a given round $\overline{p}_{t,u}$ when she has still $u \geq 1$ units to purchase prior to T. This value will be such that the bank is indifferent between buying one unit now at the smallest of all quoted prices or delaying the purchase to the future. Specifically, we will construct the upper reservation price recursively. In the last round, clearly $\overline{p}_{T,u} = v \ \forall u \geq 1$. For the previous rounds, it is useful to define the expected value at time t of future surpluses to the bank who still needs to acquire u units, $J(t,u)$. We define it

the Eurosystem, who requests quotes from multiple dealers for every, standard size notional, bond trade.

recursively.

$$J(T,u) = \mathbb{E}[\hat{s}^1_{T,u} + \ldots + \hat{s}^u_{T,u}] \ \forall u > 0 \tag{35}$$

$$J(t,u) = \mathbb{E}[\hat{s}^1_{t,u}] + \beta(1-(1-\eta)^N)J(t+1,u-1) + \beta(1-\eta)^N J(t+1,u) \ \forall u > 0 \text{ and } \forall t < T \tag{36}$$

The first equation states that in the last round if the bank still has u units to buy she gets the expected surplus of the u highest order statistics. The second equation says that if in a previous round t she has still u units to buy then the expected surplus is the expected surplus of the lowest price quoted in this round plus the expected discounted surplus from purchasing $u-1$ units in future rounds if a trade occurred in this round, or u units otherwise.[39]

Then the maximum price the bank will be willing to pay in any rounds $t < T$ solves the indifference condition (with the definition $J(t,0) = 0$):

$$\overline{p}_{T,u} = v \ \ \forall u > 0 \tag{37}$$

$$v - \overline{p}_{t,u} + \beta J(t+1,u-1) = \beta J(t+1,u) \ \forall u > 0 \text{ and } \forall t < T \tag{38}$$

One can show that the maximum prices have the following recursive structure (with the definition $\overline{p}_{t,0} = v$):

$$\overline{p}_{T,u} = v \ \ \forall u > 0 \tag{39}$$

$$v - \overline{p}_{T-1,u} = \beta\mathbb{E}\left[\sum_{j=1}^{u} \hat{s}^j_{T,u} - \sum_{j=1}^{u-1} \hat{s}^j_{T,u-1}\right] \tag{40}$$

$$v - \overline{p}_{t,u} = \beta\mathbb{E}\left[\hat{s}^1_{t+1,u} - \hat{s}^1_{t+1,u-1} + (1-\eta)^N(v - \overline{p}_{t+1,u}) + (1-(1-\eta)^N)(v - \overline{p}_{t+1,u-1})\right] \quad \forall t < T-1 \tag{41}$$

[39] Note that this expression assumes that it is always optimal for the bank to purchase a unit in the current round if a price is actually quoted by some dealer, but this turns out to be optimal given that in equilibrium dealers quote only prices from $[\underline{p}_{t,u}, \overline{p}_{t,u}]$ and the definition of the upper bound $\overline{p}_{t,u}$.

To fully characterize the equilibrium, it remains to compute $\mathbb{E}[\hat{s}^j_{t,u}]$ $\forall j = 1, \dots, u$. Define

$$\hat{H}^j_{t,u}(v-p) := Prob(\hat{s}^j_{t,u} \leq v-p) = \sum_{k=0}^{j-1} C^k_N (\eta H_{t,u}(p))^k (1-\eta H_{t,u}(p))^{N-k} \tag{42}$$

Note that[40] $\hat{H}^j_{t,u}(v-\underline{p}) = 1$ and $\hat{H}^j_{t,u}(v-\overline{p}) = \sum_{k=0}^{j-1} C^k_N \eta^k (1-\eta)^{N-k}$. We can then compute the expected surplus of the j^{th} unit purchased in round t as:

$$\mathbb{E}[\hat{s}^j_{t,u}] = -\int_{\underline{p}}^{\overline{p}} (v-p) d\hat{H}^j_{t,u}(v-p) \tag{43}$$

$$= -[(v-p)\hat{H}^j_{t,u}(v-p)]^{\overline{p}}_{\underline{p}} - \int_{\underline{p}}^{\overline{p}} \hat{H}^j_{t,u}(v-p)\, dp \tag{44}$$

$$\tag{45}$$

We have now fully characterized the equilibrium and can illustrate some of its properties. We solve the model numerically and show in figure 8 below some of the characteristics of the equilibrium price dynamics depending on some of the model parameters. The different panels show how the support of the quoted prices change through the trading rounds $[\underline{p}_t, \overline{p}_t]$ for different values of η, i.e., the ex-ante probability that a dealer quotes a price in a given round, and different assumptions about the realized trading, i.e., whether ex-post a dealer actually quoted a tradable price in a given round. Panels (a) and (b) have lower $\eta = 0.1$ compared to panels (c) and (d) with $\eta = 0.9$. And Panels (a) and (c) assume not a single trade occurs (that is no dealer quotes a price) prior to maturity. Instead panels (b) and (d) assume that one trade occurs (i.e., at least one dealer quotes a price) in period $t = 5$.

Comparing the panels we see that a very high $\eta = 0.9$, which implies that on average 9 dealers quote a price in every round, essentially leads to the competitive outcome, in that the pricing range is very narrow and close to zero (except for the last period where by definition $\overline{p}_T = 1$). Further, the dynamics of trading do not have a large impact on the trading price, that is panels (c) and (d) are very similar. Instead, if $\eta = 0.1$, which implies that few dealers expect to be quoting a price in any given round, then the price pattern is very different. Indeed, panel (a) and (b) show that in this case the price range increases significantly towards maturity. This pattern reflects the fact that

[40] Since $H_{t,u}(\underline{p}) = 0$ and $H_{t,u}(\overline{p}) = 1$.

early on dealers quote lower prices as they know they compete with future dealers. But that effect erodes as we approach maturity. Thus dealers' rents increase as we approach maturity. Further, comparing panel (a) and (b), we see that after a trade which reduces the target inventory of the bank, the pricing range drops, which shows that dealers' rents decrease with the target inventory. So market competitiveness increases with η and decreases with U the target inventory.

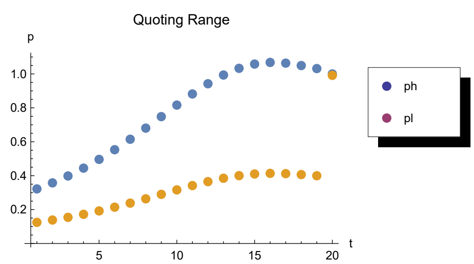
Surprisingly, we see that when the market is not very competitive (panels (a) and (b)), the maximum price ($\overline{p}_t$) at which the bank is willing to purchase a unit can exceed her reservation value of $v = 1$ as maturity approaches. While at first counter-intuitive, this phenomenon is best explained by considering a simpler two period example. Suppose that the bank wants to purchase 2 units in 2 periods from 2 dealers, who quote with probability 1 in every period. Suppose her reservation value is 1 per unit, so that if the bank enters period 2 and still needs to buy 2 units, then both dealers will quote a price of 1, since they are guaranteed to each sell their unit to the bank. Instead, if the bank enters period 2 and only needs to buy 1 unit, then Bertrand competition between the dealers will drive the price to 0. Thus the bank has an incentive in period 1 to pay up to $2 - \epsilon$ to buy one unit from the quoting dealer, so as to obtain the low price in the second period and thus reduce the total cost of purchasing the 2 units to $2 - \epsilon$. Depending on the parameters of the model, and on the realized inventory path, the bank may thus have an incentive to pay a price higher than its last period reservation value, to avoid giving too much market power to the dealers in the final rounds.

5 Empirical analysis

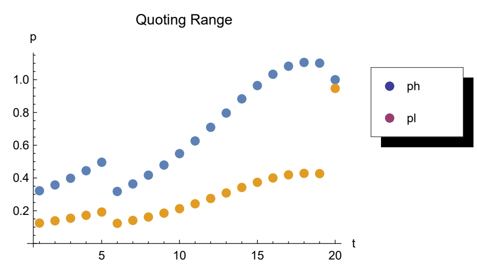
The previous section showed that a model with imperfect competition is qualitatively able to generate the pattern of rapidly increasing prices towards maturity that we document is present during the PSPP around end-of-month. In this section, we test several additional qualitative predictions of our model to further establish the link between the price anomaly, the PSPP, and the degree of competition among bond dealers.

Figure 8. The four panels show the time pattern of the quoting range $[\underline{p}_t, \overline{p}_t]$ for different trading scenarios and different level of competition (η). Parameters are $T = 20$, $U_0 = 5$, $N = 10$, $v = 1$. The No-trade scenario assumes that not a single dealers quotes a price throughout $t \in [0, T = 20]$ (so units that remain to be purchased are $U_t = U_0 = 5\ \forall t$). Instead, the Trade scenario assumes that one trade occurs in period 5 (so $U_t = U_0 - \mathbf{1}_{t \geq 5}$).

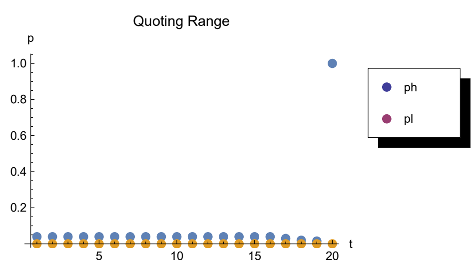
(a) Low $\eta = 0.1$, No Trade



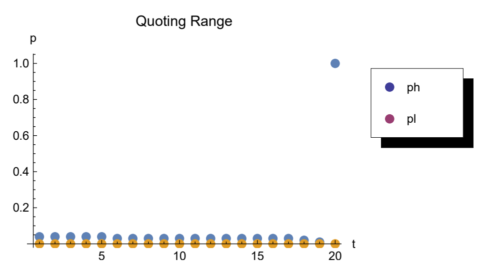
(b) Low $\eta = 0.1$, Trade



(c) High $\eta = 0.9$, No Trade



(d) High $\eta = 0.9$, Trade



5.1 Is the price anomaly linked to the Eurosystem's purchases?

The first prediction we test is whether bond prices increase over the trading rounds as we approach the end-of-month. We run a regression where we measure the impact of Eurosystem purchases on a specific bonds at day t within window j relative to the bonds that were not purchased:

$$\begin{aligned} \mathrm{Y}_{i,j,t} - \mathrm{Y}_{i,j,-9} = \gamma \times \mathrm{D.Purchase}_{i,j,t} + \sum_{t=-8}^{T=10} \alpha_t \times \mathrm{D}_t \\ + \sum_{t=-8}^{T=10} \beta_t \times \mathrm{D.Purchase}_{i,j,t} \times \mathrm{D}_t + \gamma_{i,j} + \epsilon_{i,j,t} \end{aligned} \tag{46}$$

where $\mathrm{D.Purchase}_{i,j,t}$ is a dummy variable that is equal to one when bond i is purchased at day t in window j and otherwise zero. We control for bond-window fixed effects.[41]

The pattern of the β_t coefficients confirms and strengthens our previous results (see Figure 9). We find a visible negative and large effect at the end-of-month: the yield of purchased bonds decreases more than the yield of non-purchased but eligible bonds as we approach the end-of-month. Interestingly, the yield's minimum relative to the beginning of the window is reached two days before the end-of-month. This coincides with the last day in a given month on which Eurosystem trades count towards the monthly purchase targets since it takes two business days to settle the trade.

[41] Standard errors are clustered at bond-window level.

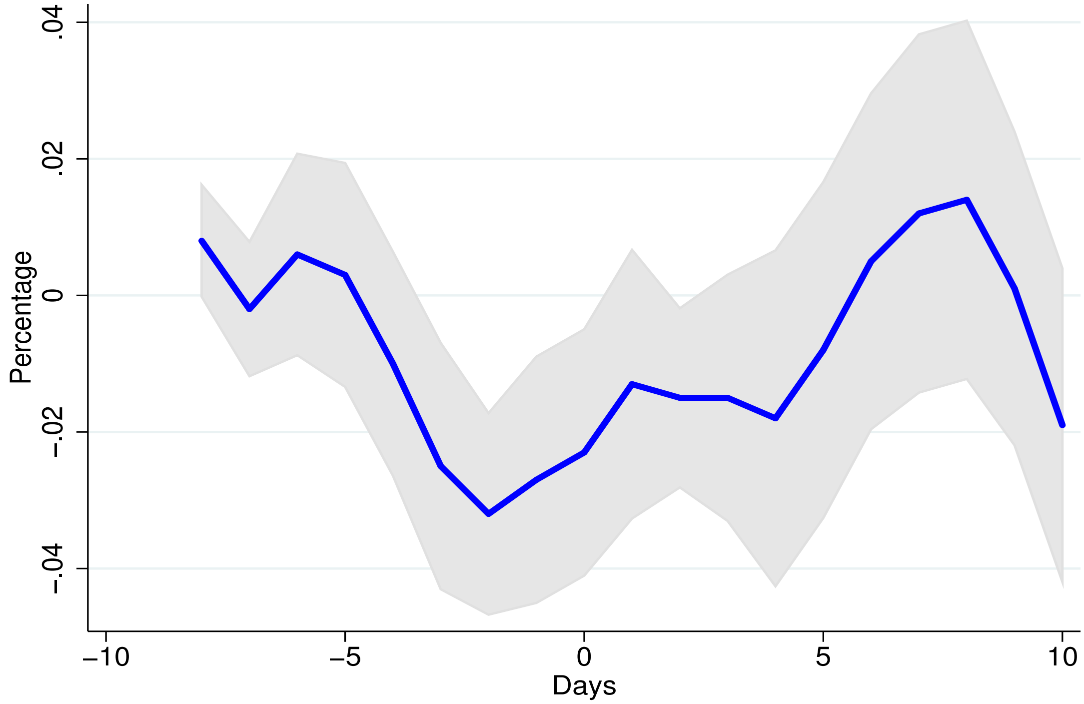


Figure 9. Eurosystem purchases and yields around end-of-month. The figure plots the interaction coefficients β_t from an OLS regression. The dependent variable is $Y_t - Y_{-9}$ where Y_t is the yield on day t with t ranging from -9 to 10 (including $t = 0$) and $t = 0$ being the last day of the month. The main independent variable is the interaction of the dummy variable D.Purchase$_{i,j,t}$, that is equal to one when bond i is purchased at day t in window j and otherwise zero, and daily indicator variables. Shadow area is confidence intervals at 95%.

We now study the determinants of the purchase decision D.Purchase by the Eurosystem. A key and distinctive feature of the PSPP is that securities purchased have to fulfill a set of eligibility criteria. We specifically look at two main eligibility criteria: the deposit rate floor rule and the blackout period. Therefore, we define a bond i as eligible for purchase at day t with an indicator variable Eligible$_{i,t}$ that is equal to 1 if the yield of bond i at day t is above the ECB deposit facility rate and/or the bond i is not subject to the blackout period that affects newly issued or reissued bond in an auction and bonds with similar residual time-to-maturity of the auctioned bond (Arrata et al. (2020), De Santis and Holm-Hadulla (2020)).

We start with a panel regression where the independent variable D. Purchase$_{i,t}$ is an indicator variable that is equal to 1 if bond i is purchased at day t and zero otherwise and the dependent variable is Eligible$_{i,t}$. Table 3 reports the results. Column (1) shows that the probability of a German sovereign bond being purchased by the Eurosystem is on average 50% due to the eligibility criteria. In Column (2), we control for bond and day fixed effects and the economical and statistical significance of the coefficient on $\text{Eligible}_{i,t}$ is slightly larger. In Column (3), we distinguish between the two main eligibility criteria: the deposit rate floor rule and the blackout period. For the latter one we use two indicator variables defining the bond as ineligible when is issued or reissued, $\text{Ineligible}_{i,t}$- bond auctioned, and is a close substitute of the auctioned bond, $\text{Ineligible}_{i,t}$- close substitute. As expected, both $\text{Ineligible}_{i,t}$ variables have a statistically and economically significant negative coefficients on purchase decision. Finally, we include the bid-ask spread and the special repo rate of the bond i at day t as additional measures that could affect the purchase decision (Column (4)). The coefficients of these two additional measures are statistically insignificant. Overall, our results suggest that the daily purchase decision is mainly affected by the eligibility criteria that are unique to the Eurosystem as an investor compared to other large investors.

Table 3. Bonds purchased by the Eurosystem and eligibility - This table reports the results of the panel regression where the independent variale D. $\text{Purchase}_{i,t}$ is an indicator variable that is equal to 1 if bond i is purchased at day t and zero otherwise. The panel regression includes bond and day fixed effects in Columns $(2)-(4)$. Standard errors are two-way clustered at date and bond levels (Columns $(2)-(4)$). Standard errors are reported in parentheses. $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1)	(2)	(3)	(4)
$\text{Eligible}_{i,t}$	0.504***	0.544***		
$\text{Eligible}_{i,t}$ - deposit rate rule			0.529***	0.539***
$\text{Ineligible}_{i,t}$ - bond auctioned			-0.496***	-0.479***
$\text{Ineligible}_{i,t}$ - close substitute			-0.428***	-0.418***
$\text{Bid-ask spread}_{i,t}$				-0.521
$\text{Special repo rate}_{i,t}$				-0.032
Observations	15,831	15,831	16,601	15,343
R-squared	0.2389	0.3420	0.3329	0.3374
Bond FE	No	Yes	Yes	Yes
Day FE	No	Yes	Yes	Yes

After the regression analysis, Figure 10 provides a box-whisker plot of the ratio of the amount of bonds purchased in a day over the total amount of bonds purchased in the same window. The figure draws a box ranging from the first to the third quartile with a line at the median. The "whiskers" going from the box to the adjacent values are the highest and lowest values that are not farther from the median than 1.5 times the interquartile range. If the Eurosystem buys the same amount of bonds every day, the ratio should be 5%(= 1/20 days). We observe that the median is 4.79% and therefore it lies slightly below this target. The figure shows that the distribution across the days is pretty stable indicating that the Eurosystem maintains a continuous market presence throughout the window with the exception of the end-of-month. Interestingly, the trading activity clearly drops in days −3 and −2 in some windows suggesting that the decrease in the Eurosystem trading activity may be linked to the run-up in bond prices quoted by the dealers.

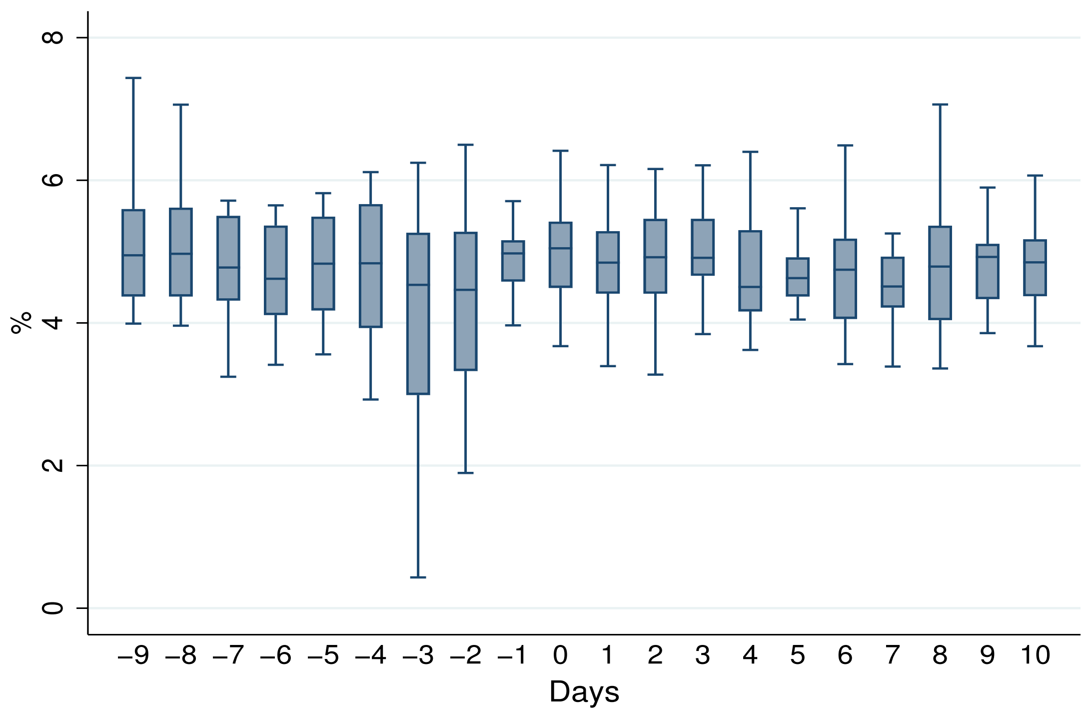


Figure 10. Eurosystem trading activity within window. The figure provides a box-whisker plot of the ratio of the amount of bonds purchased in a day t over the total amount of bonds purchased in the same window. The figure draws a box raging from the first to the third quartile with a line at the median. The "whiskers" going from the box to the adjacent values are the highest and lowest values that are not farther from the median than 1.5 times the interquartile range. t ranges from −9 to 10 (including $t = 0$) and $t = 0$ being the last day of the month.

5.2 Is the price anomaly stronger when Eurosystem trades with less dealers?

We investigate now whether the degree of competition among dealers is linked to the price anomaly. The model predicts that the lower the competition, the higher the price increase over the trading rounds as we approach the end-of-month.

To test this prediction we first count the number of counterparties the Eurosystem traded with during the last five trading days of the month within each window. Focusing on the median of this measure, we compare windows with a lower number of counterparties with windows with a higher number of counterparties. We estimate the following regression:

$$
\begin{aligned}
Y_{i,j,t} - Y_{i,j,-9} = \gamma \times \text{D.Few Dealers}_j + \sum_{t=-9}^{T=10} \alpha_t \times \mathrm{D}_t \\
+ \sum_{t=-9}^{T=10} \beta_t \times \text{D.Few Dealers}_j \times \mathrm{D}_t + \gamma_{i,j} + \epsilon_{i,j,t} \qquad (47)
\end{aligned}
$$

where D.Few Dealers_j is a dummy equal to 1 when window j has a number of dealer that are counterparties to the Eurosystem below the median. We control for bond-window fixed effects.[42]

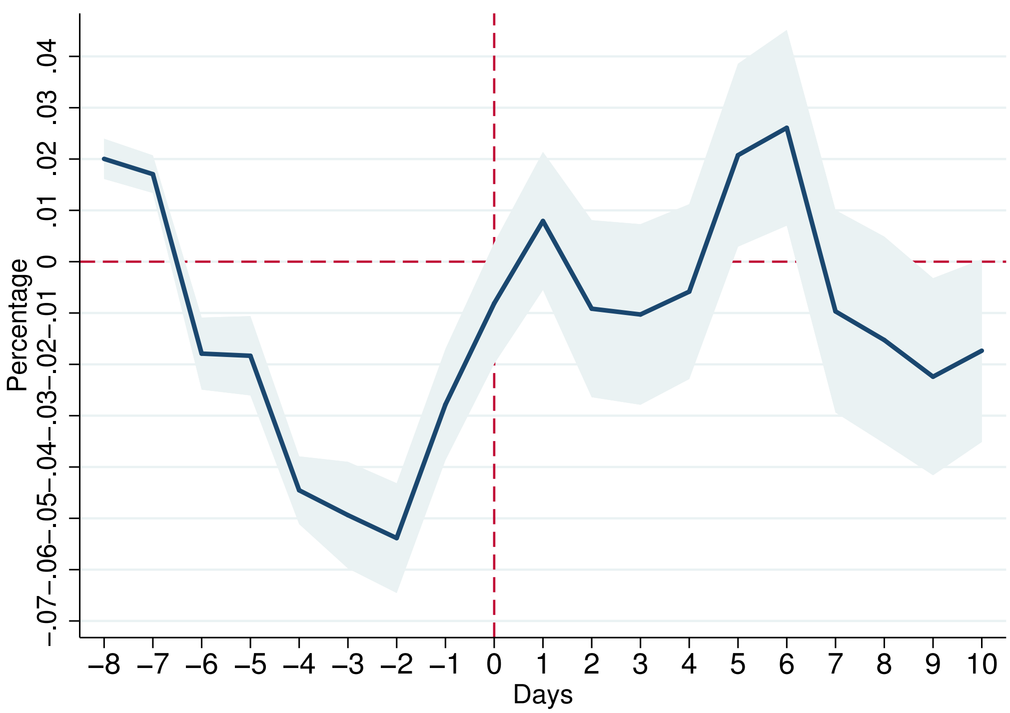


Figure 11. Degree of competition and yields around end-of-month. The figure plots the interaction coefficients β_t from an OLS regression. The dependent variable is $Y_t - Y_{-9}$ where Y_t is the yield on day t with t ranging from -9 to 10 (including $t = 0$) and $t = 0$ being the last day of the month. The main independent variable is the interaction of the dummy variable D.Few Dealers_j, that is equal to 1 when window j has a number of dealers of executed trades below the median, and daily indicator variables. Shadow area is confidence intervals at 95%.

[42] Standard errors are clustered at both bond and window level.

The pattern of the β_t is consistent with our model prediction: the lower the number of counterparties the Eurosystem trades with, the more the bond yield (price) decreases (increases) as we approach the end-of-month. After the end-of-month, we find no visible differences in the impact of the number of counterparties the Eurosystem trades with on the yield differential.

5.3 Is the price anomaly more evident when the Eurosystem buys more?

We now test a third prediction of the model: bond prices should increase more when the central bank has to buy a larger number of bonds. To test this prediction we look at windows where Eurosystem increased purchases, explicitly deviating from the monthly fixed target.

To motivate this analysis we use this statement by Benoit Couere, ECB board member, on 18 May 2015: *"Against this background, we are also aware of seasonal patterns in fixed-income market activity with the traditional holiday period from mid-July to August characterised by notably lower market liquidity. The Eurosystem is taking this into account in the implementation of its expanded asset purchase programme by moderately* **frontloading** *its purchase activity in May and June, which will allow us to maintain our monthly average of 60 billion, while having to buy less in the holiday period."*[43]

Thus, Eurosystem increased the amount of purchases in the two windows before the summer (mid-May to mid-June and mid-June to mid-July 2015 and 2016) and the window before the end-of-year (mid-October to mid-November 2015 and 2016). We re-estimate Equation (46) on the *"front-loading"* windows. We also control for bond-window fixed effects.

Figure 12 shows a more pronounced asymmetric pattern around the end-of-month in the front-loading windows, compared to the full sample estimates. Our results suggest that the Eurosystem on average paid a higher price at the end-of-month when they increased purchases due to front-loading implementation.

[43] See `https://www.ecb.europa.eu/press/key/date/2015/html/sp150519.en.htm`.

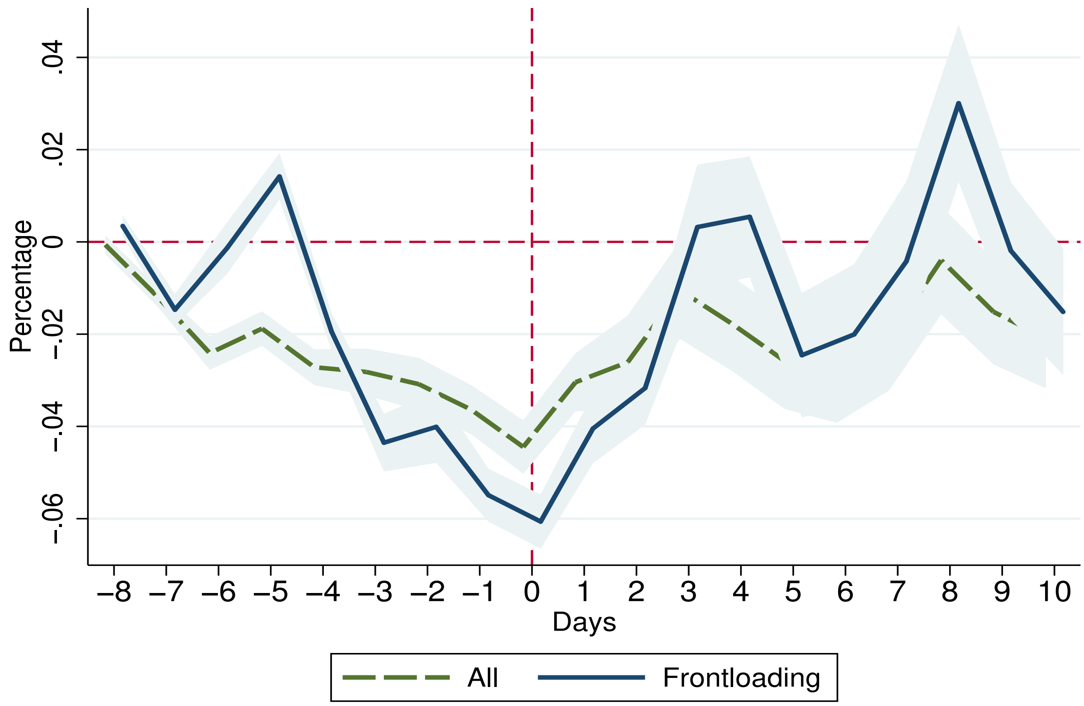


Figure 12. Frontloading and yields around end-of-month. The figure plots the coefficients α_t from an OLS regression. The dependent variable is $Y_t - Y_{-9}$ where Y_t is the yield on day t with t ranging from -9 to 10 (including $t = 0$) and $t = 0$ being the last day of the month. The main independent variable is daily indicator variables. Shadow area is confidence intervals at 95%. The continuous line indicates the point estimates when we restrict our sample to the front-loading windows. The dashed line indicates the full sample point estimates.

Moreover, we note that the more pronounced asymmetric pattern in the front-loading windows emphasizes that the price anomaly we document is not linked to bond market liquidity conditions. Figure 13 shows the evolution of German sovereign bond market liquidity indicators for two maturity buckets from Tradeweb.[44] The Germany $5.5 - 11.5$ year bucket indicator is the liquidity benchmark in the euro area and is based on German sovereign bonds that have a time-to-maturity between 5.5 and 11.5 years. An increase in the liquidity indicator points to a deterioration of bond market liquidity conditions. The figure shows a clear pattern in German bond market liquidity as pointed out by Benoit Couere. There is a decline in market liquidity from mid-July to August

[44]The sovereign Tradeweb liquidity indicators are euro area country specific. They are based on executed prices and volume data from the Tradeweb platform comparing the executed price to the mid price at security level. The distance from the mid price is used as a bond market liquidity measure: values further away from the mid price are seen as less liquid. Each index is derived from the duration weighted yield (in basis points) difference from Tradeweb composite mid prices across all trades. The Germany $5.5 - 11.5$ year bucket is selected as the liquidity benchmark. This bucket is defined as 1 at the start of the index on 2 January 2008. On the same date a multiplier is calculated on all other bucket indexes to reflect their relative liquidity level.

2015 and 2016 and from mid-November to December 2015 and 2016. Indeed, this decline in bond trading liquidity is the reason for the ECB's 'front-loading' decision. Nevertheless, we find that the pattern is more pronounced during the front-loading periods, when bond markets are more liquid. Thus the pattern is unlikely to be due to the traditional microstructure price-impact mechanisms.

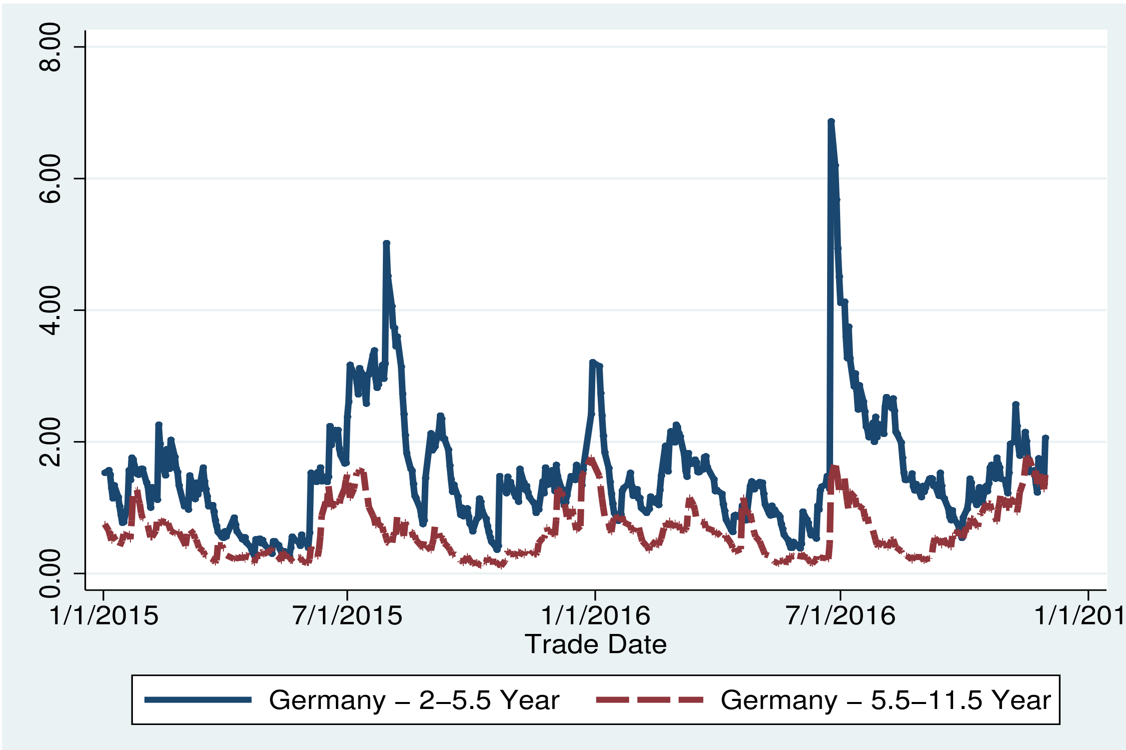


Figure 13. Tradeweb sovereign bond market liquidity indicators for German sovereign bonds (maturity bucket $5.5 - 11.5$ year and $2 - 5.5$ year)

5.4 Impact of bond prices increasing at the end of the month

To assess the economic impact of bond prices increasing at the end of the month for the Eurosystem, we perform the following calculation. First, we compute the real portfolio as the overall amount of purchases from day -9 to day 0 for each window as

$$\sum_{t=-9}^{T=0} \sum_{i=1}^{U_t} w_{i,t} \times p_{i,t}$$

where $w_{i,t}$ is amount purchased of bond i at day t by the Eurosystem at day t, $p_{i,t}$ is the Bloomberg price and U_t is number of bonds purchased at day t.

Second, we compute the beginning-of-period portfolio as the total nominal amount of purchases from day -9 to day 0 times the bond prices we observe at day -9 as[45]

$$\sum_{t=-9}^{T=0} \sum_{i=1}^{U_t} w_{i,t} \times p_{i,-9}.$$

The difference between the two portfolios

$$\Delta P = \sum_{t=-9}^{T=0} \sum_{i=1}^{U_t} w_{i,t} \times p_{i,t} - \sum_{t=-9}^{T=0} \sum_{i=1}^{U_t} w_{i,t} \times p_{i,-9} \tag{48}$$

provides an estimate of the impact of bond prices changing at the end of the month on the Eurosystem. This measure is inspired by the implementation shortfall approach (Perold (1988)). This computation is a standard metric in market microstructure to measure the extent to which markets are illiquid. Measuring an expected shortfall does not imply a market loss for the Eurosystem and does not necessarily mean that the Eurosystem could purchase the entire desired amount at the initial price.[46]

Figure 14 plots ΔP for each window (as percentage of the real portfolio) for German sovereign bonds. The figure also plots the differential yield between the average yield of German bonds at day -9 and the average yield of the same bonds at day 0 for each window. A positive differential yield points to a yield (price) decrease (increase). We expect a negative impact for Eurosystem when the yield differential is positive. Overall, we observe a positive ΔP indicating that the price anomaly we document occurs in most of the windows. Interestingly, we also observe a certain variation in our measure over time. Based on our estimates, the impact due to the difference in prices of German sovereign bonds is on average euro 12.3 million per month of the market value of the securities purchased in the last 10 days of each month. The total yearly impact amounts to euro 148 million during our sample period.

[45] An alternative approach would be to compute the measure using the executed prices by Eurosystem instead of the Bloomberg quotes. However, the executed prices at time -9 are not available for all the securities purchased over the 10$-$day period to compute the second leg because Eurosystem does not buy all the securities on each day t.

[46] Because markets are not perfectly, infinitely liquid and deep, the average price at which an investor transacts a desired quantity may deviate from the initial price at which she starts to transact.

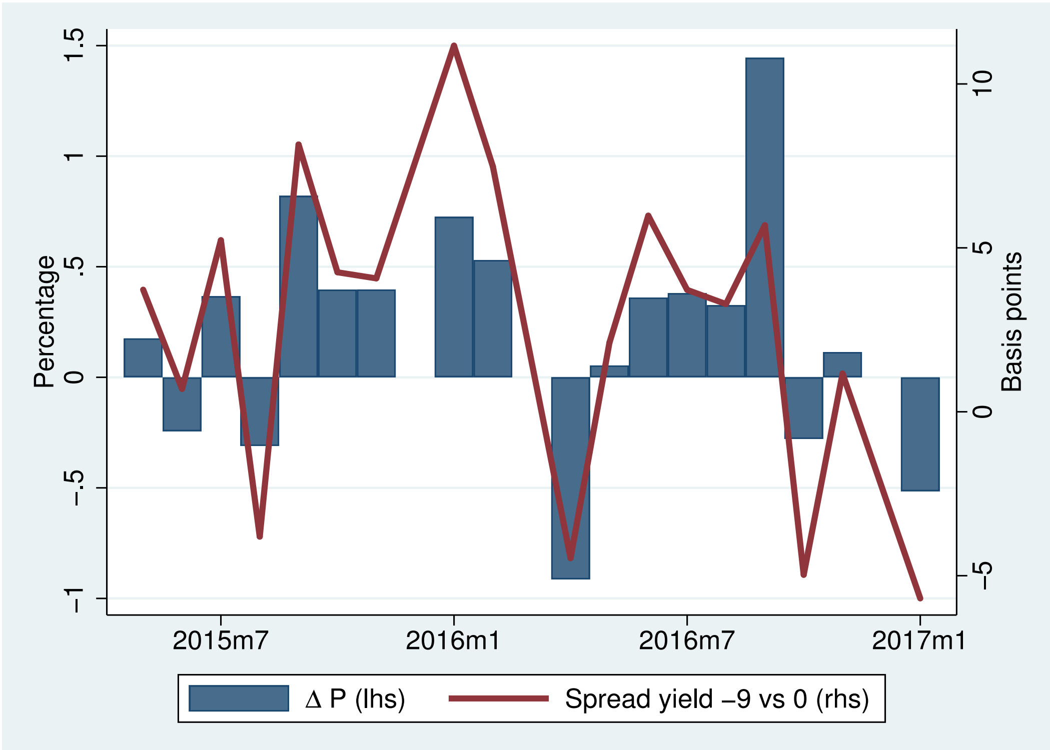


Figure 14. The figure plots the difference between the real portfolio, as the overall amount of purchases from day −9 to day 0 for each window, and the beginning-of-period portfolio, calculated as the total nominal amount of purchases from day −9 to day 0 times the bond prices we observe at day −9, as percentage of the real portfolio (left-hand side). The figure also plots the differential yield between the average yield of German bonds at day −9 and the average yield of the same bonds at day 0 for each window (right-hand side).

6 Conclusions

We show that during the implementation period of the ECB's PSPP, the prices (yields) of German sovereign bonds targeted by the PSPP increase (decrease) predictably towards month-end and drop (increase) subsequently from March 2015 to February 2017. This pattern is more pronounced, (i), on days and for bonds which are being purchased by the central bank at the time, (ii) in 'front-loading' months when the central bank purchases more (outside the summer and December periods which are typically less liquid), (iii), in months when the central bank trades with fewer counterparties, and, (iv), at quarter-ends, when more constrained banks are less likely to act as intermediaries.

Our empirical results are consistent with a simple sequential search-bargaining model where the central bank buys several units over several trading rounds. With imperfect competition among dealers, dealers' bargaining power and their expected rents increase as end-of-month approaches.

Our findings have potential implications for the design of asset purchase programs. First, the results suggest that the Eurosystem should consider moving away from committing to fixed euro notional purchases at fixed dates originally introduced to strengthen the perception that the ECB was resolute in executing the PSPP (Rostagno et al. (2021)). The implicit monthly purchase target for a large country as Germany can increase the price pressure effect by giving more bargaining power to dealers towards each end-of-month. One way to ease such a constraint could be to have no purchase target at all or to define the amount as a total envelope over a longer period similarly to the ECB's PEPP.

Second, the Eurosystem should consider moving towards trading on broader platforms open to a larger number of counterparties to encourage more competition from other natural sellers. Although some Eurosystem national central banks have used reverse auctions to target specific securities under the PSPP (Hammermann et al. (2019)), one could imagine setting up regular auctions possibly via some centralized electronic trading platform at Eurosystem level as a useful trading mechanism to have in place. On this platform, all dealers, not limited to the national central bank's counterparties, could supply their quantities available for purchase by the Eurosystem. This platform could be opened up to other large institutional investors (such as large insurance companies or buy-side firms) who might also be available to trade their inventory of fixed-income securities. In particular, in times of market stress, a more "open" trading platform might be useful as the central bank can act as a "buyer of last resort" (Duffie (2020)). It would also help alleviate less competitive pricing by dealers that are constrained in their intermediation capacity at specific points in time, such as around quarter-ends and year-ends due to regulatory requirements (Breckenfelder and Ivashina (2021)). A careful cost-benefit analysis should be conducted to assess the feasibility of such measures.

Finally, the Eurosystem modified the PSPP eligibility criteria to face the shortage of German sovereign bond securities. Expanding the set of securities eligible for PSPP purchases at the end of 2016 increased the availability of targetable securities potentially limiting the bargaining power of dealers at the end of the month. We leave the analysis of such changes to the PSPP to future research.

A-I Appendix

Table A-I. Robustness - Bond holding returns and yields around the end-of-month - This table reports the coefficients of the regression where the dependent variable is i) the bond holding return $\log(P_{i,j,t}/P_{i,j,-9})$; and ii) the bond yield $Y_{i,j,t} - Y_{i,j,-9}$, where $P_{i,j,t}$ ($Y_{i,j,t}$) is the price (yield) of the bond i at day t of window j (from -9 to 10) and $P_{i,j,-9}$ ($Y_{i,j,-9}$) is the price (yield) of the same bond on the end-of-window day ($t = -9$). The independent variable is day t, with t ranging from -9 to 10 (including $t = 0$), and $t = 0$ being the end-of-month day. The regression includes bond x window fixed effects (Columns (1) – (5). Standard errors are clustered at bond x window level. Standard errors are reported in parentheses. $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1) Yield - Swap rate	(2) Return	(3) Return	(4) Return	(5) Return
		Exclusion close substitute bonds	Exclusion auctioned bonds & close substitute bonds	Exclusion bond enters benchmark index	Exclusion ineligible bonds
-8	-0.001**	-0.004	0.001	-0.000	-0.001
-7	-0.003***	0.109***	0.107***	0.110***	0.161***
-6	-0.007***	0.199***	0.199***	0.195***	0.264***
-5	-0.004***	0.130***	0.136***	0.134***	0.186***
-4	-0.005***	0.215***	0.212***	0.219***	0.300***
-3	-0.008***	0.219***	0.210***	0.214***	0.292***
-2	-0.009***	0.221***	0.214***	0.220***	0.293***
-1	-0.008***	0.279***	0.268***	0.270***	0.378***
0	-0.012***	0.347***	0.327***	0.333***	0.469***
1	-0.008***	0.179***	0.163***	0.170***	0.249***
2	-0.002	0.108	0.098	0.106	0.156
3	-0.002	-0.056	-0.065	-0.055	-0.064
4	-0.004	0.009	-0.002	0.006	0.020
5	-0.008	0.079	0.071	0.075	0.118
6	-0.009*	0.074	0.057	0.070	0.111
7	-0.010*	-0.018	-0.029	-0.019	-0.010
8	-0.007	-0.187*	-0.192*	-0.182*	-0.218
9	-0.011**	-0.085	-0.096	-0.085	-0.083
10	-0.016***	-0.039	-0.048	-0.033	-0.015
Obs.	14,412	12,933	12,593	14,172	10,652
R-squared	0.4618	0.4679	0.4657	0.4746	0.4771
Bond - Window FE	Yes	Yes	Yes	Yes	Yes

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