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Scarcity effects of QE: a transaction-level analysis in the Bund market

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Non-technical summary

Research Question

This paper investigates the impact of the ECB/Eurosystem's Public Sector Purchase Program (PSPP) on prices and liquidity of German Treasury securities, in short Bunds. Our focus is on the scarcity effects of the asset purchases and possible market distortions.

Contribution

This is the first study that matches high-frequency data on official-sector asset purchases with high-frequency inter-dealer sovereign bond data. This enables a precise identification of the intra-day impact of bond purchases via scarcity effects. Due to the presence of a large unidirectional buyer, potential demand-supply imbalances may arise. The impact of such imbalances on the market functioning, especially liquidity provision, are studied in detail.

Results

The results of this study show significant and positive price impacts of PSPP purchases on Bunds, both at the minute and daily frequencies. This highlights the importance of scarcity in bond markets. These intended price effects are not without side effects. We find that large-scale asset purchases affect liquidity conditions in the Bund market. Standard liquidity measures such as bid-ask spreads and order book depth suggest a decline in market quality. We further show that price impacts depend on market conditions. They are substantially higher in times of market stress and during episodes of high yields, when the demand for government bonds is suppressed.

Nichttechnische Zusammenfassung

Fragestellung

In dieser Studie untersuchen wir, welchen Einfluss das durch die EZB/das Eurosystem seit März 2015 implementierte Staatsanleiheankaufprogramm (PSPP) auf die Kurse und Liquidität von Bundesanleihen hat. Dabei liegt unser Fokus auf Knappheitseffekten und möglichen Marktverzerrungen, welche durch die Kaufvolumina an den Anleihemärkten ausgelöst werden.

Beitrag

Im vorliegenden Papier werden erstmals hochfrequente Daten eines Zentralbankankaufprogramms mit Daten eines elektronischen Handelssystems zwischen Geschäftsbanken zum Handel von Staatsanleihen kombiniert. Dadurch können Kurseffekte der Staatsanleihekäufe minutengenau analysiert werden. Aufgrund der umfangreichen Wertpapierkäufe, die im Rahmen des PSPP durch die Bundesbank durchgeführt werden, können Ungleichgewichte im Markt für Bundesanleihen entstehen. Die Auswirkungen solcher Ungleichgewichte auf das Funktionieren des Marktes, insbesondere Verzerrungen der Liquidität, werden innerhalb dieser Studie detailliert beleuchtet.

Ergebnisse

Die Ergebnisse der Studie lassen auf signifikante Kurseffekte der PSPP-Käufe auf Bundesanleihen schließen, sowohl auf Minuten- als auch auf Tagesbasis. Demnach scheinen durch das Kaufprogramm bedingte Knappheitseffekte durchaus relevant zu sein, was den Wirkungsmechanismus der Maßnahmen betrifft. Diese beabsichtigten Kursseffekte sind allerdings auch mit Nebenwirkungen verbunden: Gängige Liquiditätsmaße, wie die Geld-Brief-Spanne und die Tiefe des Orderbuchs, weisen auf verschlechterte Liquiditätsbedingungen hin. Weiterhin verdeutlichen die Ergebnisse, dass der Kurseffekt mit den Marktbedingungen variiert. So zeigen Staatsanleihekäufe die größten Effekte in Perioden, in denen der Markt angespannt ist, sowie in Phasen erhöhter Anleiherenditen, wenn die Nachfrage nach Staatsanleihen allgemein geringer ist.

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Abstract

This paper investigates the scarcity effects of quantitative easing (QE) policies, drawing on intra-day transaction-level data for German government bonds, purchased under the Public Sector Purchase Program (PSPP) of the ECB/Eurosystem. This paper is the first to match high-frequency QE purchase data with high-frequency inter-dealer data. We find economically significant price impacts at high (minute–by–minute) and low (daily) frequencies, highlighting the relevance of scarcity effects in bond markets. Asset purchase policies are not without side effects, though, as the induced scarcity has an adverse impact on liquidity conditions as measured by bid-ask spreads and inter-dealer order book depth. We further show that the price impact varies greatly with market conditions: it is considerably higher during episodes of illiquidity and when yields are higher.

Keywords: Quantitative Easing, European Central Bank, Scarcity Channel, Bond Market Liquidity, High-Frequency Data.

JEL classification: E52, E63, G11, G12, H63.

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1 Introduction

This paper empirically studies how central bank asset purchases affect bond prices and liquidity via their impact on the relative scarcity of securities. We answer this question with granular German government bond data for purchases under the Public Sector Purchase Program (PSPP) of the ECB/Eurosystem. With its decision to conduct broad-based purchases of sovereign debt on January 22, 2015, the ECB followed other major central banks in conducting large scale asset purchases with the aim to achieve its price stability objectives and stimulate the economy.[1] The PSPP is designed such that there is little uncertainty about the monthly bond purchase amounts and eligible securities. Despite the lack of uncertainty about the overall quantitative purchase targets, we find economically significant contemporaneous price effects of PSPP purchases at high (minute–by–minute) and low (daily) frequencies, suggesting that scarcity effects are important in government bond markets.

To assess the impact of PSPP purchases on prices and the functioning of bond markets, security-level data is required. Standard event studies focusing on announcements effects suffer from the fact that the introduction of the policies may not come as a pure surprise to market participants. This issue is particularly severe in the case of the ECB's PSPP which was anticipated since late 2014. The main advantage of this study is that the data at our disposal contain time-stamped information on actual purchases of securities at the ISIN-level. We link these intra-day and proprietary over-the-counter purchase data with data from the MTS trading platform, the main inter-dealer venue for EUR-denominated sovereign bonds.[2] This allows a precise identification of the intra-day impact of bond purchases via scarcity effects, effectively eliminating alternative explanations for the purchase effect, which commonly plague event studies. To our knowledge, the data used in this study is the most granular in terms of its intra-day availability and security-by-security information.

Our empirical setup not only allows for a detailed analysis of the mechanism through which supply-demand imbalances created by the presence of a large unidirectional buyer exert on bond prices, but also enables us to study its impact on market functioning. The impact of asset purchases on liquidity conditions in fixed income markets is under-

[1] Prior to embarking on QE via PSPP, the ECB had relied on a series of other unconventional monetary policy tools, mostly geared towards addressing banks' strained funding conditions as the European sovereign debt crisis escalated (e.g. Long-Term Refinancing Operations – LTROs, haircut policies) or to repair the broken transmission channel of monetary policy (Securities Markets Program – SMP, Outright Monetary Transactions – OMT etc.).

[2] The MTS trading venue (Mercato dei Titoli di Stato MTS) – now part of the London Stock Exchange Group – was originally established in 1998 under the auspices of the Bank of Italy and Ministry of Finance and quickly emerged as the main wholesale trading venue for German and other European sovereign bonds.

studied in the extant literature, mostly due to a lack of granular data on purchases and high-frequency transaction-level bond market data. This paper fills this gap.

Obtaining a deep understanding of the mechanism through which unconventional policies work and its possible side effects is crucial from both an academic and a policymaker perspective. A common way to think about the impact of QE on the yield curve is via the "signalling" and the "portfolio balance" channel. According to the former, market participants will immediately adjust their expectations about the future course of monetary policy at the time of announcement. There will be no additional price impact of the actual purchases themselves, as their role is merely to give credibility to the central bank in its promise to keep monetary conditions accommodative for an extended period of time (see e.g. Woodford (2012), Christensen and Rudebusch (2012), Bauer and Rudebusch (2014)). The portfolio balance channel, by contrast, posits that bonds of different maturity and other characteristics are not seen by investors as perfect substitutes. By affecting the relative scarcity of safe government bonds at different maturities, central bank asset purchases induce fixed income investors to switch to riskier substitutes (longer duration and or lower credit). Greenwood and Vayanos (2010, 2014), Krishnamurthy and Vissing-Jorgensen (2012), Krishnamurthy and Vissing-Jorgensen (2013) and others emphasize the importance of supply constraints of safe assets as a key to understand asset pricing phenomena in fixed income markets.

Besides the quantification of the price impact of QE, our paper sheds light on local supply effects and preferred habitat theories of the term structure more broadly. It is usually very difficult to precisely gauge the price impact of supply and demand shocks on the term structure, due to the fact that shifts to the supply and demand for bonds happen infrequently (Greenwood and Vayanos, 2010). Our data allow us to identify a series of repeated exogenous shocks in the form of ex-ante specified central bank purchases of bonds with different maturities and characteristics. This represents an ideal natural experiment to study whether supply shocks have persistent effects on prices or whether they may create any distortions for market liquidity.

Our paper focuses on purchases of German Treasury bonds, implemented by Deutsche Bundesbank under the auspices of the ECB/Eurosystem. German Treasury securities are unique in that they are one of the few remaining AAA-rated European sovereign bonds and are generally accepted by market participants as a risk-free benchmark.[3] If the PSPP has an impact on the highest quality sovereign bonds in the Euro area, it will also affect all other Euro area sovereign bonds that are priced off of the German yield curve.

We study the intra-day response of bond prices to central bank purchases based on a

[3]The German 10-year bond, typically called the Bund, serves as the benchmark for long-term financing and as the underlying for the Bund-Future, the most traded and liquid fixed income future in Europe.

VAR setup in the spirit of Hasbrouck (1991), estimated over the period 10 September 2015 to 31 October 2016. The results show that bond prices respond swiftly to central bank asset purchases. We estimate an immediate (5-minute) price impact of a typical asset purchase of about 1.6 basis points on average. PSPP purchases are performed akin to over-the-counter (OTC) transactions. The price details of the trade are only known to the central bank and the counterparty in the trade. Hence, it is ex-ante unclear how long it takes for the information to be reflected in market prices. MTS market-wide prices show that on average the information that a bond has been purchased by the Bundesbank takes roughly 5 minutes to be fully-impounded into prices. We also find that "central bank order flow" appears to have a persistent effect, in that the prices do not reverse in subsequent minutes. To our knowledge, these findings on a delayed trade information revelation to the broader market are novel to the literature.

In the second part of our analysis, we study the impact of PSPP purchases on prices and liquidity in a daily panel regression setting. The analysis is performed at a daily frequency over the sample period from 9 March 2015 to 31 October 2016. Depending on the exact specification, we estimate daily price effects of purchases of between 1 basis point and 3 basis points. When taking into account the size of the PSPP purchase volume, we find large and statistically significant price effects of between 2 and 6 basis points per EUR 100 million purchased. The effect is independent of other known drivers of bond prices, e.g. movements in the slope of the yield curve and risk appetite. The daily and intra-daily impacts are of comparable size (1.6 basis points versus 2.2 basis points for specification (1) per EUR 100 million) showing that the effects survive even after controlling for time–series and cross–sectional effects.

Beyond their impact on prices, the scarcity effects of asset purchases, can have adverse side effects on market functioning, too. For instance, the presence of a large unidirectional buyer can impact liquidity by exhausting dealers' capacity to bear risk. To alleviate the PSPP's impact on market functioning, the Eurosystem has made bonds available for lending as of April 2nd, 2015. Our results suggest that this may not be enough to address the liquidity strains in the market.[4] We obtain these results by studying the impact of central bank purchases on market liquidity in affected securities, an area which has received little attention in the literature so far. Using order book data, we construct high-frequency liquidity measures. Our analysis focuses on the (relative) bid-ask spread and order book depth as the best measures of the cost to buy and sell a small amount of a security, in line with other recent work on measuring bond market liquidity (e.g. Schestag, Schuster, and Uhrig-Homburg, 2015). Understanding the impact of official

[4]However, since the end of our observation period on 31 October 2016 the Governing council has already decided to improve the conditions for securities lending significantly.

sector purchases on market functioning and quality in fixed income markets is highly relevant from a policy perspective, especially against the backdrop of changing nature of intermediation in fixed income markets in recent years (e.g. CGFS, 2014; MC, 2016; CGFS, 2016).

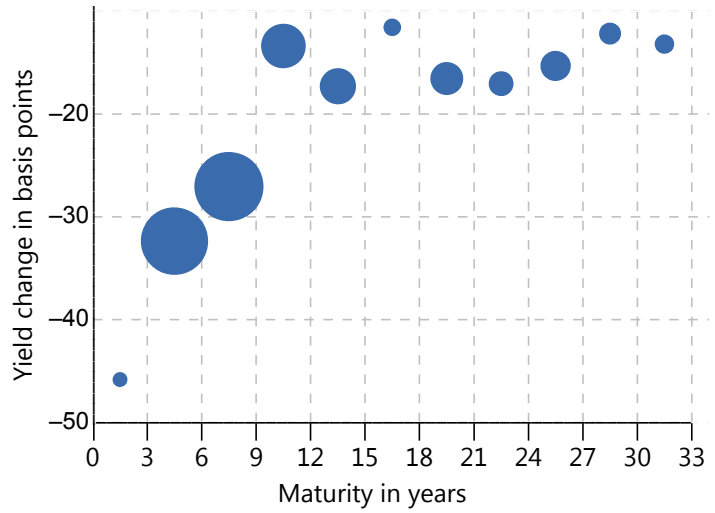
We find a negative relationship between PSPP purchases and market-wide liquidity, both in a longer time–series and in a daily regression framework. Over the course of the program, bid–ask spreads have increased and depth has decreased overall. And, these effects have been more visible in bonds purchased under the program. The adverse impact of asset purchases on Bund market liquidity are confirmed in our panel regression setup as well. The (relative) bid–ask spread for purchased bonds scaled by purchase volume is between 4 and 8 basis points higher than for bonds not purchased on that particular day.

We further study the market conditions during which central bank asset purchases have a higher impact. This should be informative for central banks when deciding about timing of purchases in specific securities to best effect policy goals. We repeat the price impact analysis conditioning on liquidity and yield levels. Our high-frequency and daily results show that the price impact of central bank asset purchases is significantly greater on days when markets are illiquid. Additionally we investigate price impacts conditional on yields. One particular example of high yields during our sample period is the Bund Tantrum, however, we look at the impact of yield levels more generally.[5] Our findings suggest that central bank price impact at high-frequency tends to be about 1/3 larger in periods when yields are above their sample mean. These results therefore suggest that the price impact of purchases is highly state-dependent.

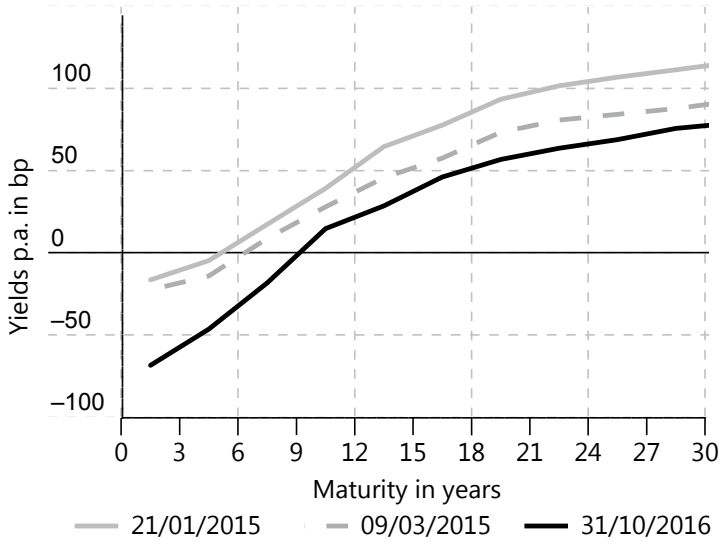
The focus of this paper is on the direct impact of asset purchases (scarcity) on prices and market liquidity, rather than investigating the total effects of the program involving a variety of transmission channels. While our data do not permit perfect identification of the permanent and cumulative effects of PSPP purchases, they allow us to provide an estimate. Figure 1 plots the change in yields, and a representation of the purchase volume across maturities. It shows that the fall in yields is most pronounced in maturities with high purchase volumes. The figure also shows that yields fell uniformly between the announcement of the PSPP and the first PSPP purchase. The yield curve as of October 31st, 2016, the end of our sample period, is substantially lower at the short end of the yield curve, and the curve is much steeper than before or at the start of the program. The cumulative effects of the scarcity effects of the program thus appear to have been significant.[6] For instance, between the announcement of the program on January 22, 2015

[5] See e.g. Riordan and Schrimpf (2015) for an analysis of liquidity conditions during the Bund Tantrum.

[6] One needs to point out that of QE was not the only policy measure affecting the yield curve over the course of the programme, of course. For instance, there were also changes to the rate on the deposit facility over the period. In our formal regression analysis we control for the related events.



(a) Yield changes and purchases by maturity segment



(b) Yield curve shift over the course of the PSPP

Figure 1: The top-panel figure shows the volume of German government bonds purchased by the Bundesbank within the PSPP in 3-year maturity segments of the yield curve as well as the yield change in that particular yield curve segment since the inception of the PSPP, from 9 March 2015 to 31 October 2016. The size of the bubbles represents the purchased volume within the study period. It shows that the drop in yields is more pronounced in the front end, the segment which has also been featuring larger purchase volumes. The bottom-panel shows the yield curve configuration for different dates. It provides an indication of the relevance of signalling vs the scarcity effect of the purchases.

and the day of the first PSPP purchase on March 10, 2015 average Bund prices increased 92 basis points. Based on our estimates of the price impact (between 2.2 and 6.1 basis points per EUR 100 million PSPP purchase) we estimate that the purchase program has lead to an increase in German treasury prices between 78 and 218 basis points. This suggests that purchase effects are important in terms of size relative to announcement effects.

To understand the effect in terms of yields we take a 10-year German treasury bond with a maturity of February, 2025, annual coupon of 0.5% a price of 101.68 (as of March 31st, 2015), and a yield–to–maturity of 33 basis points (DE000110237). An increase in the bond price by 218 basis points (from 101.68 to 103.90), our maximum estimate, leads to a 22 basis point decrease in the yield to 11 basis points. This estimated impact is sizable given that – unlike QE1 and QE2 of the Federal Reserve or the ECB's other unconventional policies – ECB purchases via the PSPP occur during a period of extraordinarily low interest rates and volatility. In fact, large parts of the Bund yield curve shifted into negative territory at the announcement of the program, and (with the exception of a few spells of market turbulence in mid-2015) they remained negative throughout.

The paper proceeds as follows. Section 2 provides a brief review of the related literature. Section 3 details the institutional features of the ECB's PSPP program and gives an overview of the data on PSPP purchases and MTS inter-dealer trading of Bunds. Section 4 reports the main empirical results on the price impact of QE. We first focus on the effects of QE at high-frequency, before turning to the analysis based on daily data. Section 5 investigates the impact of asset purchases on bond market liquidity. In Section 6, the mechanisms of the price effects are examined in more detail. Section 7 concludes.

2 Literature Review

The implementation of QE has by now been extensively investigated in a series of papers on the Federal Reserve's large-scale asset purchase programs, including inter alia, (Gagnon, Raskin, Remache, and Sack (2011); Krishnamurthy and Vissing-Jorgensen (2011); Wright (2012); D'Amico and King (2013); Christensen and Rudebusch (2012); Meaning and Zhu (2012); Kandrac and Schlusche (2013); Bauer and Rudebusch (2014)).[7] These studies broadly find supporting evidence for both the signalling and portfolio re-

[7]Quantitative easing and unconventional policies have also been found to have an impact beyond bond markets on financial conditions more broadly. By inducing a switch to riskier assets, the polices have contributed to a compression in credit spreads (Krishnamurthy and Vissing-Jorgensen, 2011; Gilchrist and Zakrajsek, 2013), in turn alleviating funding strains of firms in the wider economy. They have also been found for example to trigger sharp movements in capital flows (Fratzscher, Duca, and Straub, 2012), alleviate crash risk (Hattori, Schrimpf, and Sushko, 2016) and raised bond and equity prices of constrained financial sector intermediaries (Chodorow-Reich, 2014).

balancing channels of QE discussed above.[8] Due to a lack of granular data, however, many empirical papers on QE have resorted to event study techniques with announcement effects. Yet, as QE policies over time became more widely accepted as part of the central banking toolkit and became more widespread, the surprise element of QE-related announcement may have dissipated (e.g. Meaning and Zhu, 2011; McLaren, Banerjee, and Latto, 2014). It seems fair to say, that expectations of further policy action were increasingly priced in by market participants, attenuating the impact of the news at the time of the actual policy announcement. Our paper, by contrast, directly looks at the impact of purchases and hence is not subject to this commonly voiced criticism of event studies based on announcement effects.

Key insights have also been gleaned from studies on unconventional polices by other major central banks. Joyce, Lasaosa, Stevens, and Tong (2011), Joyce and Tong (2012), and McLaren et al. (2014) find a significant impact of the Bank of England's quantitative easing policies on Gilt prices. Krishnamurthy, Nagel, and Vissing-Jorgensen (2015) study the impact of ECB's unconventional policies (LTROs, SMP, OMT) based on an event study approach, aimed at quantifying the contribution of various transmission channels. They attribute most of the drop in yields on peripheral euro area sovereign bonds following the introduction of the ECB policies to a reduction in default risk. In a similar vein, Eser and Schwaab (2016) find that ECB asset purchases of Greek, Irish, Italian, and Portuguese debt securities via the SMP led to significant reduction in their yields. Even though it also involved asset purchases by the central bank, the SMP was not designed as a QE program, but was mostly concerned about undoing the changes in the transmission channel of monetary policy which was heavily affected as the European sovereign debt crisis had escalated. Altavilla, Carboni, and Motto (2015) study the effects of the ECB's PSPP on a range of asset prices, shedding light on various transmission channels. In contrast to Krishnamurthy et al. (2015) Altavilla et al. (2015) and Eser and Schwaab (2016), our focus is exclusively on the German government bond market which serves as the benchmark curve in the euro area. And, we examine the direct impact of actual purchases of securities at high and low frequencies rather than the impact of a set of policy announcements.

A distinct feature of our work is to study the impact of asset purchases from a microstructure perspective. In this regard, the paper that is closest to ours is D'Amico and King (2013), which also look at purchases of individual securities (albeit at a daily frequency). Breedon and Turner (2016) investigate gilt purchases by the Bank of England with a focus on the mechanism through which the purchases are conducted and the associated transaction costs. Most recently Song and Zhu (2016) use Federal Reserve re-

[8] See Borio and Zabai (2016) for a comprehensive literature review.

verse auction purchase data and find that purchase prices tend to be above corresponding market offer prices, suggesting that purchases may induce demand-supply imbalances in the Treasury market. Similarly to our paper, Dunne, Hau, and Moore (2014) and Pelizzon, Subrahmanyam, Tomio, and Uno (2016) investigate the structure of bond trading, liquidity provision and market functioning on the MTS inter-dealer platform. Kandrac (2014) examines the effects of the Fed's large scale asset prices on market functioning and liquidity in the MBS market. D'Amico, Fan, and Kitsul (2014) investigate how scarcity effects of asset purchases affect pricing in special collateral repo markets. Finally, Christensen and Gillan (2016) study the impact of the large-scale asset purchases on liquidity premiums embedded in TIPS prices.

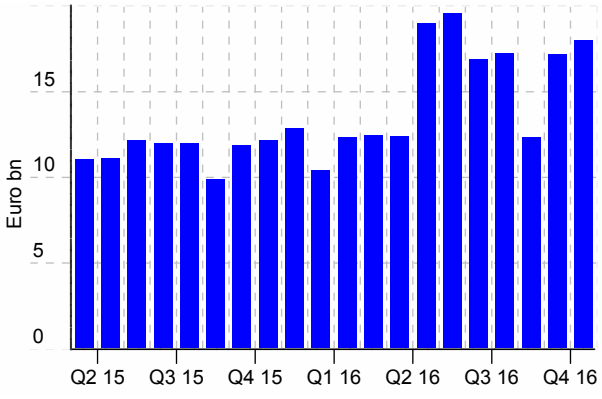
Our paper differs from earlier work in three ways: First, to our knowledge, this is the first paper with intra-day time-stamped information on actual official sector asset purchases to estimate the price impact of QE. Second, we study the impact of quantitative easing on market functioning and market quality, a highly relevant topic but hitherto largely unexplored. Third, we focus on the impact of QE during a relatively stable financial market period unlike most other papers which mostly looked at the impact during episodes of severe financial stress.

3 Markets and Data

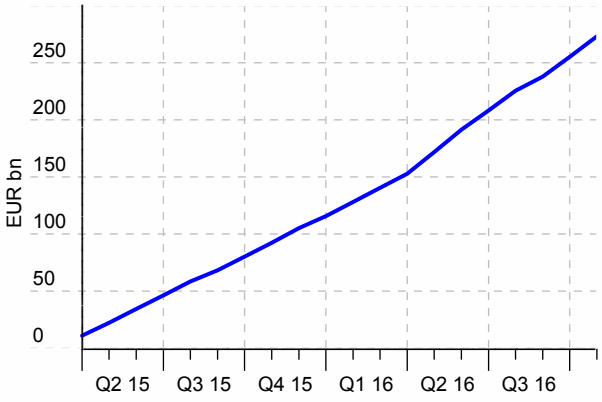
3.1 Background and PSPP Implementation

On January 22th 2015, the ECB Governing Council announced an expanded asset purchase program (APP) aimed at fulfilling the ECB's price stability mandate. The program added the purchase of public sector bonds to the already existing private sector asset purchase programs of asset backed securities (ABS) and covered bonds. Asset purchases were designed to combat deflation and provide monetary stimulus in an environment where interest rates had fallen to their effective lower bound (ELB). The Governing Council took this decision in a situation in which most indicators of actual and expected inflation in the euro area had drifted towards their historical lows. It was decided that the entire APP, also including the ABS purchase program (ABSPP) and the covered bond purchase program (CBPP3), should equal roughly EUR 60 billion per month.[9] The PSPP purchases are distributed across euro area jurisdictions according to the ECB's capital key, with national central banks focusing exclusively on purchases in their home market. Within the home market, the respective central bank retains some flexibility with regard to the choice of securities to be purchased (e.g. central government or agency securities).

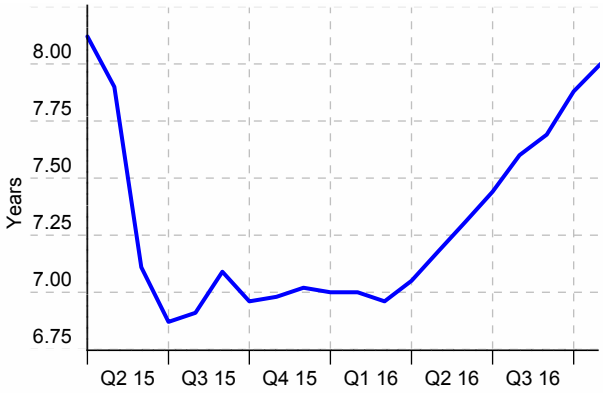
[9]Whereas the PSPP is by far the main driver of the programs with a total volume of EUR about 1,148 billion at the end of October 2016, the CBPP3 is expected to account for the main part going forward.



(a) Volume



(b) Cumulative Volume



(c) Average Maturity

Figure 2: The top-panel figure shows monthly aggregates of the volume of German securities purchased under the PSPP from 09 March 2015 to 31 October 2016, expressed in EUR billion. The depicted volume includes all purchases, independent of the respective bond type. The centre-panel Figure depicts monthly aggregates of the cumulated purchased volume, expressed in EUR billion. The bottom-panel Figure shows the evolution of average maturity of the purchased securities.

The PSPP initially targeted bonds issued by euro area central governments, recognized agencies and European institutions in the secondary market. On December 3rd 2015, together with the decision to expand the purchase period to at least March 2017, the Governing Council decided to include EUR-denominated marketable debt instruments issued by regional and local governments located in the euro area in the list of eligible assets. Expanding the set of securities eligible for PSPP purchases was intended to enhance the flexibility of the program and thereby support its continued smooth implementation. In its decision on March 10, 2016 the Governing Council further decided to expand its purchases to EUR 80 billion per month starting in April 2016. At the same time, it also announced a new program for corporate bonds (CSPP) starting from June 8, 2016.

Figure 2 plots monthly aggregates of the daily average of all German securities purchased under the PSPP program. Monthly purchases roughly range from EUR 10 billion to EUR 20 billion. The centre panel plots the cumulative purchases from program inception until October 2016. The bottom panel plots the average maturity of purchased securities over the life of the PSPP, ranging from below 7 to roughly 8 years. While these figures also include ECB purchases of German securities as well as agency and regional bonds bought by the Bundesbank, the following analysis is limited to the purchases of German securities by the Bundesbank alone. These cover the vast majority of purchases and provide us with accurate intra-day information.[10]

The PSPP requires the maturity of purchased bonds to be between 2 years and 30 years and 364 days. Yields on purchased bonds must be above the rate on the ECB's deposit facility at the time of purchase.[11] The Eurosystem intends to "conduct purchases in a gradual and broad–based manner, aiming to achieve market neutrality to avoid interfering with the market price formation mechanism". Additionally, portfolio managers avoid bonds that are expensive, e.g. trading special in repo markets. However, especially for German bonds a large part of the outstanding supply has yielded lower than the rate on the ECB's deposit facility during large parts of the program, restricting the bonds available for purchase.

[10]The detailed numbers for this limited purchase universe cannot be shown due to confidentiality reasons.

[11]On December 8th 2016 (after our sample period) the Governing Council decided to include bonds with maturity between 1 and 2 years and with yields below the deposit facility in the program "to the extent necessary". With this decision shortage in purchasable bonds should be compensated as at the same time it was announced to prolong the program again from end of March 2017 to at least end of December 2017. However monthly purchase volume was decreased again from EUR 80 bn per month back to the initial EUR 60 billion starting from April 2017.

3.2 PSPP Purchases of German Treasury Securities

Table 1 compares the characteristics of PSPP bond purchases against the outstanding universe of bonds as of 31 October 2016. We report average coupons, yields, years since issuance and remaining maturity. Bonds purchased via the PSPP program have higher yields and coupons, were issued earlier and have a higher remaining maturity than bonds not purchased.

For the sake of completeness, Table 1 also presents details on inflation-linked securities, which are not studied further in the paper, however. Inflation-linked bonds are not subject to the deposit facility restriction. Yields on purchased linkers are below those of the outstanding universe. The most notable difference is that the yields on inflation-linked securities are well below the deposit facility rate, suggesting that purchases in these securities may act as a release valve at times when the remaining supply of purchasable non-inflation linked securities is tight.

Table 1: Bond Characteristics

	Nominal		**Inflation-linked**	
	PSPP	Outstanding Universe	PSPP	Outstanding Universe
Coupon in % p.a.	2.79	2.08	0.80	0.68
Yield in % p.a.	-0.07	-0.26	-1.07	-0.92
Years since issuance	7.30	5.55	5.28	4.71
Remaining maturity in years	10.22	7.02	5.48	7.62

The table shows the characteristics of the purchased bonds in comparison to the outstanding universe of the same category of bonds as of 31 October 2016. The values given are volume-weighted averages over the universe of bonds purchased by the Bundesbank and outstanding bonds, respectively. Nominal bonds include Federal Bonds, Federal Notes and Federal Treasury Notes.

3.3 Official Sector Purchases vs. Inter-dealer Transactions

How large are official sector asset purchases when benchmarked against trading activity and transactions in the broader wholesale fixed income market? To answer this question, Table 2 reports differences between PSPP transactions of German securities and those on MTS, the main inter-dealer trading venue. MTS is an electronic bond trading platform

Table 2: Implementation of Asset Purchases

	PSPP	**MTS** *(memo)*	**Ratio**
Mean ticket size (in m Euro)	18.73	5.94	
Std. ticket size (in m Euro)	10.60	4.50	
Avg # purchases per bond and day	1.44	6.57	
# PSPP trades within best b/a quote	4,232		92%
# PSPP trades at better price	316		7%
# PSPP trades at worse price	26		1%

The table summarizes information about the ticket size of the asset purchases carried out between 10 September 2015 and 31 October 2016 and trades on the MTS platform in the same period. The three rows at the bottom include information on the pricing characteristics of PSPP purchases, i.e. whether they were carried out within best bid and ask quotes prevailing on MTS or executed at even better (or worse) prices. The exact time of a PSPP purchase is only available from 10 September 2015 until 31 October 2016.

organized around a centralized limit order book, similar to equity exchanges. We use the MTS data that provide a tick-by-tick overview of transactions and bid-offer prices.[12] MTS market participants – typically major banks' bond dealing desks – can provide liquidity by posting limit orders, and trades execute based on price and time priority. Dealers primarily rely on this venue for the purpose of managing inventory risk from accumulated positions with other counterparties. The MTS market allows for an easy calculation of inter-dealer market liquidity as laid out in Schestag et al. (2015).[13] If liquidity deteriorates in the market used by dealers for risk management purposes, one is likely to see spillovers to the dealer-customer segment as well.

To estimate the effects of the PSPP on market prices and liquidity, we merge the PSPP transaction data with the MTS transaction and quote data. Since an accurate intra-day time stamp (1-minute frequency) of the Bund purchases carried out by the Bundesbank is available only from 10 September 2015 on, our empirical analysis is based on two different datasets. For the daily analysis of price and liquidity effects, we use the data since the inception of the PSPP, from 9 March 2015 to 31 October 2016. For the intra-day analysis

[12] We focus on liquidity in the Euro-Bond-Market segment (EBM) rather than the local (GER) segment as the EBM is the inter-dealer market representing the best available and immediately executable prices.

[13] Similar to other OTC markets, sovereign bond markets feature a two-tier structure, consisting of an inter-dealer segment at the core and a dealer-customer segment (see, e.g., Bech, Illes, Lewrick, and Schrimpf, 2016, for more details).

of price effects, our sample period ranges from 10 September 2015 to 31 October 2016.

Official sector asset purchase transactions tend to be relatively large on average and less frequent compared to those among participants in the wholesale market, as Table 2 shows. PSPP trades are roughly three times the size of a typical transaction between private wholesale market participants via the MTS platform. A bond purchased via the PSPP is purchased roughly once per day. On MTS, by contrast, there are on average about 6 transactions per day for a typical German bond. The standard deviation of ticket (trade) size on MTS is also much lower than the ticket size for an average PSPP purchase.

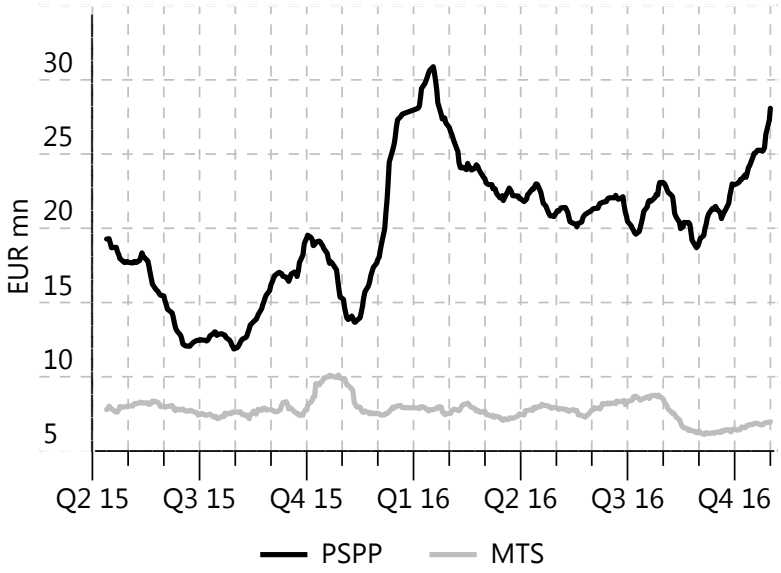


Figure 3: The figure shows the evolution of the average ticket size of transactions in Bunds, given in EUR million, since the start of the PSPP program in March 2015 until October 2016. The blue line indicates the average ticket size of purchases by the Bundesbank within the PSPP program, the red line depicts transactions of Bunds within the MTS market.

It is also interesting to inspect information on trade execution for PSPP purchases. We find that 92% of all official sector purchases during our review period are within the currently available bid-ask spread on MTS (Table 2). In 7% of the cases, the transactions even take place at a price below the best bid price. Thus, overall 99% of the time the trades are conducted at prices that are better than those on the main inter-dealer venue.

In Figure 3 we show how the ticket size evolves over time for the PSPP and for interbank transactions on MTS. In the early part of the program, PSPP ticket sizes are roughly twice those on MTS. In the latter half of the program they are roughly 3.5 times larger. The large increase in PSPP ticket sizes appears to be driven by a sharp rise mid-

Table 3: Descriptive Statistics by Maturity Segment

	Short-term	Medium-term	Long term	Ultra long-term
Bond characteristics				
PSPP purchases				
Coupon in % p.a.	2.26	1.95	2.85	4.25
Yield in % p.a.	-0.62	-0.38	0.03	0.56
Years since issuance	5.47	4.90	8.83	10.55
Remaining maturity in years	2.49	5.47	9.63	21.52
Outstanding volume				
Coupon in % p.a.	1.68	1.75	1.83	4.06
Yield in % p.a.	-0.76	-0.41	0.10	0.68
Years since issuance	4.83	4.47	5.40	9.81
Remaining maturity in years	1.54	5.22	9.34	22.35

The table shows descriptive statistics of German government bond purchases under the PSPP by the Bundesbank between 9 March 2015 and 31 October 2016, broken down by maturity. It compares the purchased and the outstanding volume (as of 31 October 2016) broken down into short (0–3.5 years), medium (3.5–7.5 years), long (7.5–12.5 years), and ultra long-term bonds (>12.5 years).

way through our sample period, when the size of the APP was increased from EUR 60 to 80 billion per month. While not particularly pronounced, there appears to be a drop of the average MTS ticket size later in the program. This latter observation suggests that market participants may be having difficulties executing large volumes on MTS, a possible indication of strained liquidity conditions.

In Table 3 we present descriptive statistics as of October 31st, 2016, across four maturity categories, (1) short-term, (2) medium-term, (3) long-term, and (4) ultra long-term. Short-term bonds have a maturity between 0 and 3.5 years, medium-term have a maturity between 3.5 and 7.5 years, long-term bonds are between 7.5 and 12.5, and ultra long term bonds have maturities greater than 12.5 years. We rely on this distinction by maturity buckets throughout the remainder of the paper to study price and liquidity impact of asset purchases across yield curve segments. We report coupons, yields, time since issuance, and maturity for PSPP purchases and the outstanding universe. The results show that purchased bonds are not materially different than the outstanding universe of bonds. This suggests that our results are unlikely to be driven by cross-sectional differences in purchased bonds, but rather by the time-series impact of PSPP purchases.

Table 4 compares PSPP ticket sizes with those on MTS by bond maturity. It is interesting to see that ultra long-term bonds (maturities greater than 12.5 years), in particular, exhibit much low inter-dealer ticket sizes via the MTS platform. A likely reason is that end-investors (mostly insurance companies and pension funds) buy and hold (ultra)long-dated securities to match their long-term liabilities. This leads to less liquidity and less intermediation in these segment, as captured by MTS trading data. The trading activity, especially when combining ticket size and trading frequency, tends to be much higher for short-term government paper on MTS. Additionally the results show that in our study period a large number of PSPP trades are within the best available bid-ask quotes across all bond segments.

Table 4: Implementation of Asset Purchases across the Yield Curve

	Short-term	Medium-term	Long term	Ultra long-term
PSPP trades				
Mean ticket size (in m Euro)	25.80	23.15	18.58	13.01
Std. ticket size (in m Euro)	13.37	10.58	10.03	7.41
Avg # purchases per bond and day	1.63	1.61	1.27	1.16
# of PSPP trades within best b/a quote	91%	85%	94%	98%
MTS trades				
Mean ticket size (in m Euro)	7.66	5.90	5.50	3.65
Std. ticket size (in m Euro)	6.02	3.57	3.35	1.77
Avg # purchases per bond and day	7.18	5.57	5.60	6.75

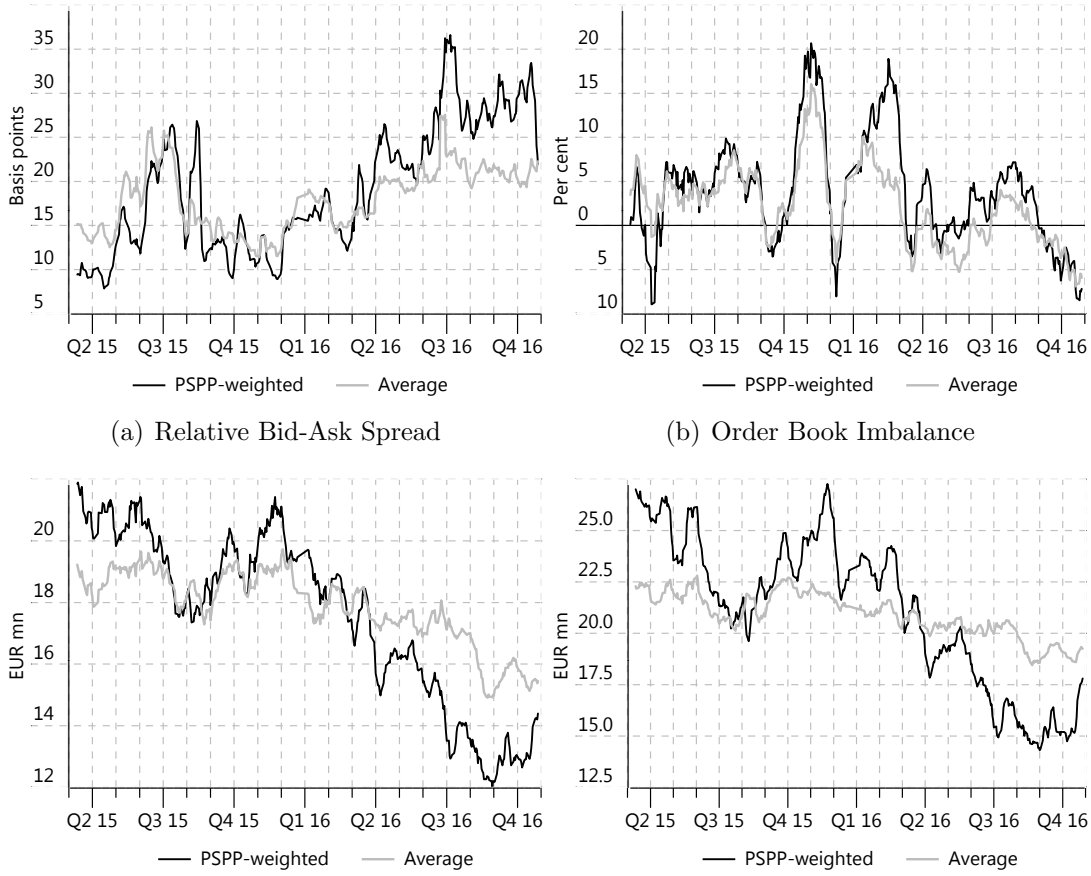
The table compares PSPP purchases by the central bank with transactions among private sector market participants on the MTS platform. The Table is set up analogously as Table 2, but broken down into short (0–3.5 years), medium (3.5–7.5 years), long (7.5–12.5 years), and ultra long-term bonds (>12.5 years). The exact time of a PSPP purchase is only available from 10 September 2015 until 31 October 2016.

3.4 Liquidity Conditions in the Bund Market

Market liquidity is an important factor when assessing the impact of official sector asset purchase programs. Not only are these metrics informative when gauging the materiality of any "side effects" of the unconventional policies, they also allow us to investigate circumstances under which the purchases are the most effective. Table 5, Panel A reports

liquidity metrics in purchased bonds, computed from high-frequency MTS order book data. Panel B also shows liquidity metrics for purchased bonds, relative to those bonds that were not purchased but eligible for purchase.

We measure liquidity in a number of ways. The bid-ask spread and the relative bid-ask



(a) Relative Bid-Ask Spread

(b) Order Book Imbalance

(c) Top Order Book Depth

(d) Average Order Book Depth

Figure 4: This figure shows different market liquidity measures for the Bund market. The red line indicates the weighted average of the measures for all four buckets, while the blue line accounts for the purchase amount in each bucket and adjusts the average accordingly. Panel a) depicts the evolution of the bid ask spread relative to the mid price since the start of the programme, given in basis points. Panel b) shows the order book imbalance, defined as difference between ask and bid quantity relative to the total volume corresponding to the best bid and ask quotes, which is given in percent. Panel c) depicts the order book depth at the best quotes, defined as the sum of volume supplied or asked at the best quotes. The measure is denoted in EUR million. Finally, panel d) provides the evolution of the order book depth which represents the average of the three best bid and ask prices, given in EUR million. Before plotting, the data are smoothed based on a two-sided 5-day moving average.

spread capture the cost to immediately purchase or sell a particular bond.[14] Depth at the best bid and ask prices and average depth at the best three available prices captures the amount of a security that can be immediately purchased.

Table 5 shows that liquidity, when measured via relative bid-ask spreads, tends to decrease with maturity. Depth, however, is fairly evenly distributed across maturities with the exception of ultra long term bonds, with roughly half the depth of medium-term bonds. Both coincide with the observation that, at least on the MTS platform, ultra-long bonds are traded much less frequently than shorter term bonds. One reason could be that older securities that trade less frequently feature a larger degree of voice intermediation (Hendershott and Madhavan (2015)), allowing dealers to negotiate over the price and other details of the transaction. Order book imbalances are positive suggesting that there is a greater quantity of securities offered for sale at the ask than dealers would be willing to buy at the bid.

When comparing purchased bonds to those not purchased, we find that transaction costs tend to be larger in those bonds that are purchased compared to those in non-purchased securities. Also, depth is lower and the order book imbalance tends to be larger. This is true across most maturities and on average. This preliminary analysis suggests that the asset purchase program may have been associated with a drop in market liquidity, at least on average during the sample period.

In Figure 4, we plot the relative bid–ask spread (a), order book imbalance (b), top of order book depth (c) and average order book depth (d) from Q1 2015 to Q3 2016. The red line is an equal–weighted average across all bonds. The blue line depicts the PSPP volume–weighted average across purchased bonds.

Relative bid–ask spread (averaged across bonds) increase over the period from roughly 15 basis points to 20 basis points, an increase by 33%. When we weight spreads across bonds by their weight in the PSPP portfolio, the rise in illiquidity is even more pronounced. For these bonds, relative bid-ask spreads have increased from roughly 10 basis points to close to 30 basis points. Turning to the quantity-based liquidity metrics, we observe that the order book imbalance measure has shown no trending behavior over our sample. The picture is quite different for top of book and average order book depth. Both quantity-based liquidity metrics have fallen significantly over the sample period. For instance, top of order book depth for volume–weighted bonds falls from EUR 20 billion to roughly EUR 12 billion. The results are similar for average order book depth.

All in all, these initial observations indicate that liquidity conditions in the Bund market have deteriorated over our sample period. The differences between equal–weighted liquidity metrics and those with weights based on PSPP portfolio shares, suggest that the

[14] The relative bid-ask spread (expressed in basis points) is given by $[(ask - bid)/mid] \cdot 10,000$.

fall in liquidity is more pronounced in purchased relative to non-purchased bonds. We examine this important issue in greater detail in Section 5 of the paper.

Table 5: Liquidity Characteristics

	b/a spread	rel. b/a spread	Depth (Best)	Depth (Avg.)	Order Book Imbalance
Panel A: Purchased bonds					
Short term (0-3.5)	6.57	6.13	19.22	22.99	22.15
Medium term (3.5-7.5)	7.78	6.91	21.75	27.89	33.81
Long term (7.5-12.5)	19.39	13.53	18.07	21.50	29.05
Ultra long term (>12.5)	65.99	41.05	11.39	11.57	14.38
Avg.	30.44	20.14	17.00	20.16	25.04
Panel B: Purchased bonds *relative* to those not purchased					
Short term (0-3.5)	1.21	1.02	-2.69	-1.86	0.09
Medium term (3.5-7.5)	-0.20	-0.22	-0.80	0.18	0.07
Long term (7.5-12.5)	1.03	0.65	-0.15	-0.03	0.01
Ultra long term (>12.5)	0.74	0.02	-0.01	-0.05	-0.00
Avg.	6.56	3.81	-1.58	-1.35	0.07

The table shows different liquidity measures for bonds purchased under the asset purchase program during the observation period from 9 March 2015 to 31 October 2016 (Panel A). The liquidity proxies include bid-ask spread in basis points, relative bid-ask spread (bid ask spread relative to the mid price since the start of the program, given in basis points), depth (measured as amount of bonds in million) at the best bid and ask price, average depth at the three best bid and ask prices as well as order book imbalance. The latter is defined as the difference of the quantity at the ask price and the quantity at the bid price divided by the sum of both and then multiplied with 100 to get a percentage. Panel B shows the difference in the liquidity of purchased securities vs those that are not purchased. The shaded area (red) indicates that the respective measure reflects worse liquidity conditions in the purchased bonds relative to the non-purchased bonds.

4 The Price Impact of QE via the Scarcity Channel

In the following, we study the impact of asset purchases on bond prices to shed light on the scarcity channel of quantitative easing based on micro-level data. First, we look at the intra-day price impact of central bank order flow based on a VAR in the spirit of Hasbrouck (1991), a classical approach in the microstructure literature. Second, we employ a panel regression approach based on daily data.

4.1 Price Impact at High Frequency

We start by studying the impact of purchases at high frequencies. This is our preferred setting as it allows for an unambiguous identification of the price impact of the central bank "order flow". To this end, we estimate a simple bivariate system as follows:

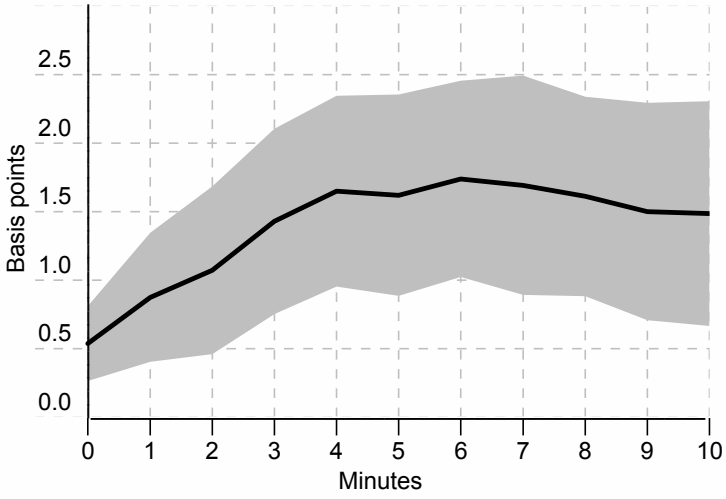
$$\begin{aligned} r_t &= a_0 + a_1 \cdot r_{t-1} + a_2 \cdot r_{t-2} + \ldots + a_{10} \cdot r_{t-10} + \\ &\quad b_0 \cdot \Psi_t + b_1 \cdot \Psi_{t-1} + \ldots + d_{10} \cdot \Psi_{t-10} + \nu_{1t} \qquad (1) \\ \Psi_t &= c_0 + c_1 \cdot r_{t-1} + c_2 \cdot r_{t-2} + \ldots + c_{10} \cdot r_{t-10} + \\ &\quad d_1 \cdot \Psi_{t-1} + \ldots + d_{10} \cdot \Psi_{t-10} + \nu_{2t}, \qquad (2) \end{aligned}$$

where $r_t = p_t - p_{t-1}$ denotes the (log) bond return and Ψ_t denotes the purchase volume of the central bank. Most of our interest lies in determining the cumulative price impact coefficient measured at 1-minute intervals and given by $\Lambda^{(N)} = \Sigma_{i=0}^{N} \widehat{b}_i$.

Figure 5 plots the cumulative price impact coefficient $\Lambda^{(N)}$ up to 10 minutes, and its associated 95% confidence bands. The graph is constructed by averaging across the price impacts of individual bonds that are obtained from VARs estimated individually for each security separately.

At the time of purchase there is an unambiguous increase in the price of the purchased bond. The price increase appears to be fairly persistent as the cumulative return increases to roughly 1.6 basis points. Prices appear to adjust to a new equilibrium price within about 5 minutes of the purchase. There does not appear to be a reversal suggesting that the upward price drift is permanent. We further analyze their persistence in our subsequent daily analysis.

What is striking is that even though the PSPP purchases are carried out bilaterally with bank dealers like OTC transactions (that is, the exact transaction details are only known to the two counterparties), they are reflected swiftly in the wider inter-dealer market. That said, when purchasing a specific security the central bank requests quotes from multiple dealers. Knowledge about not having succeeded in a bid for a transaction,



(a) Price impact on purchased bond

Figure 5: This figure shows the average intra-day cumulative price impact of PSPP purchases of German government bonds. The horizontal axis indicates the minutes elapsed after the purchase occurring at $t = 0$. The estimation of price impact is obtained based on a bi-variate VAR of (log) bond returns and public sector order flow in the spirit of Hasbrouck (1991). The estimation is performed at the level of individual bonds. The cumulated price impacts are aggregated across bonds for each step by means of a cross-sectional regression (of the price impact at the indicated lag) onto a constant. The gray lines indicate 95% confidence bands obtained from the cross-sectional regression.

thus allows non-transacting dealers to update their price quotes. Our results suggest that transacting dealers appear to quickly update their quotes in the MTS market and the remaining dealers quickly follow suit.

Table 6 reports the coefficient of PSPP purchases on returns from minute 0 to 10 after the purchase. The results show a large and instantaneous impact on bond prices of 0.54 basis points. The coefficient remains positive for a few minutes before leveling off at zero. The t-statistics are computed using HAC robust standard errors for the cumulative coefficient and show that the purchase has a statistically significant impact on prices.

Our results thus far show an unambiguous and contemporaneous impact of PSPP purchases bond prices. An important question is whether or not the overall results are similar across bonds of different maturities. Hence, we repeat the previous analysis for short-, medium-, and long-term bonds. Cumulative price impact coefficients $\Lambda^{(N)}$ are illustrated in Figure A.A.1 in the Appendix for horizons up to 10 minutes following the purchase. The speed at which the broader market reprices in the aftermath of a PSPP transaction differs across yield curve segments. Short-term bonds exhibit a relatively small response to purchases. The results are strongest in ultra long-term securities with

Table 6: Intra-day Price Impact of Asset Purchases

Minute post purch.	Coef. PSPP flow	Cum. Price Impact	CSR t-stat
0	0.54	0.54	3.98
1	0.34	0.88	3.75
2	0.20	1.07	3.54
3	0.36	1.43	4.27
4	0.22	1.65	4.78
5	-0.02	1.62	4.46
10	-0.01	1.49	3.66

The table summarizes estimation results for the intra-day price impact of PSPP flow. The second column shows the average coefficient on lagged PSPP order flow. Cumulative price impact is shown in column 3. The numbers indicate the price impact in basis points for EUR 100 million purchase volume. The right column reports the t-statistic of the null hypothesis of no aggregate cumulative price impact, based on a cross-sectional regression of cumulative price impact on a constant.

a price impact of roughly 5 basis points for a remaining maturity greater than 12.5 years after 10 minutes.

Table 7 reports the results in tabular format. Bonds in medium, long, and ultra-long term bonds all have statistically significant cumulative price impacts. By 10 minutes, the impact of PSPP bond purchases appears to have leveled off, suggesting that the purchase effect has been fully processed by the broader market.

4.2 Measuring the Price Impact of QE at Daily Frequency

We complement our intra-day analysis with a lower frequency analysis of purchase effects on bond prices similar to that conducted in extant work such as D'Amico and King (2013) and Eser and Schwaab (2016). In Section 5, we leverage the methodology to study the impact on fixed income market liquidity.

To study the impact of bond purchases on daily prices, we rely on a panel regression, which is formulated as follows

$$r_{i,t} = \alpha_i + \beta \cdot \Psi_{i,t} + \delta \cdot Controls_{(i),t} + \epsilon_{i,t}, \tag{3}$$

where r represents (log) bond price changes as before. The variable Ψ denotes the purchase

Table 7: Price impact of asset purchases by maturity

Minutes	0	1	2	3	4	5	10
Maturity segment: 0-3.5y							
Coef. PSPP flow	0.01	0.18	0.09	-0.22	0.01	0.17	0.13
Cum. Price Impact	0.01	0.19	0.27	0.05	0.06	0.23	0.59
t-stat	0.1	1.19	1.13	0.33	0.44	1.28	2.67
Maturity segment: 3.5-7.5y							
Coef. PSPP flow	0.21	0.34	0.33	0.15	0.36	-0.24	-0.06
Cum. Price Impact	0.21	0.55	0.88	1.03	1.39	1.15	1.22
t-stat	2.73	5.65	5.79	7.39	8.63	6.66	4.83
Maturity segment: 7.5-12.5y							
Coef. PSPP flow	0.39	-0.20	-0.02	0.26	0.16	0.42	-0.33
Cum. Price Impact	0.39	0.19	0.16	0.42	0.58	1.00	0.84
t-stat	2.21	1.00	0.71	1.16	1.71	6.10	2.05
Maturity segment: $>$ 12.5y							
Coef. PSPP flow	1.96	1.20	0.59	0.71	0.50	0.06	0.03
Cum. Price Impact	1.96	3.16	3.75	4.46	4.96	5.03	3.84
t-stat	4.20	5.13	4.58	5.62	9.77	8.72	4.56

The table summarizes estimation results for the intra-day price impact of PSPP flow by maturity segment. The first row in each maturity panel reports the average coefficient on lagged PSPP order flow. Cumulative price impact is shown in the row below. The numbers indicate the price impact in basis points for EUR 100 million purchase volume. Furthermore, the Table reports the t-statistic on the null hypothesis of no aggregate cumulative price impact, based on a cross-sectional regression of cumulative price impact on a constant.

dummy or the purchase dummy interacted with the purchase amount (in EUR million). T–statistics are calculated using standard errors that are clustered by bond. The reference group of bonds in this specification contains all types of Bunds that could theoretically be bought under the PSPP with the exception of inflation linked bonds ("all bonds").

In these regressions, we also control for general market volatility and risk, proxied for by the VIX, the yield spread between short-term and long-term bonds (Term), and a variable that controls for end-of-month (EoM) effects. All specifications include a variable that controls for the maturity of a bond (short-term ST, medium-term MT, and ultra long-term ULT). ST takes the value 1 if a bond has a maturity of less than 3.5 years and

zero otherwise. MT takes the value 1 if a bond matures in 3.5 and 7.5 years and zero otherwise. ULT takes the value 1 if a bond has a maturity greater than 12.5 years. Bonds that mature between 7.5 and 12.5 years (long-term LT) are captured in the constant term.

We also control for important announcement effects, in particular the ECB Governing Council meetings on December 3, 2015 and March 10, 2016. Specification (2) adds a variable that controls for whether or not a bond is "eligible" that takes the value 1 if the yield on a bond on a particular day is not below the ECB deposit facility rate (between -0.2% and -0.4%, in our sample period) and zero otherwise. Specification (3) additionally includes a dummy that takes the value 1 if the particular bond is also purchased on the previous day $(t-1)$. Specification (4) adds a variable that captures whether or not a bond is purchased multiple times on day t. Since these control variables not only depend on time t, but also on the specific bond i, the control term is denoted with an i in parentheses.

Table 8 reports regression results on the impact of a PSPP purchase on bond prices. The dependent variable is the change in log bond prices from the previous day's close $t-1$ to day t. Panel A is based on a definition of Ψ that takes the value of 1 on purchase days for a specific bond and zero otherwise. In Panel B, Ψ is given by the interaction of the purchase variable with purchase amounts and can be interpreted as the impact of a EUR 100 million purchase on the bond price.

The results can be interpreted as PSPP induced price change differences relative to all other bonds not purchased on a particular date. The results indicate a positive impact of PSPP purchases on bond prices. The impact ranges from 1.1 basis points and 3.1 basis points for purchases in Panel B. For purchase amounts, the impacts are larger and vary between 2.2 basis points and 6.1 basis points. The overall purchase impact is statistically significant for all but one of the eight specifications. The economic impact increases when controlling for bond-specific characteristics. Adding the dummy variable which accounts for purchases of the same bond on the previous day, the overall purchase effect roughly doubles. The previous purchase dummy itself exhibits a negative sign indicating that bonds which have been already purchased on the previous day do not show an equally strong price reaction on the purchase day anymore. Similarly, bonds that are purchased through multiple trades (usually between 2 and 4) exhibit a less strong price effect than than those bought via a single transaction. Particularly striking is the statistically and economically strong impact of the announcement on 3 December 2015. On that day, Bund interest rates increased significantly in response to the decision of the Governing Council meeting. This reaction probably reflects the astonishment of market participants who had expected the Eurosystem to not only extend the PSPP, but also to increase monthly purchase volumes. All in all, these results suggest that purchases have an impact at the daily frequency and are thus likely to be persistent.

Table 8: Impact of Asset Purchases on Bond Prices: Daily Analysis

	Panel A: Purchases				**Panel B: Amounts**			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Ψ	1.139*	1.261	2.893***	3.074***	2.189**	2.284**	4.188***	6.097***
	(0.683)	(0.796)	(0.977)	(1.001)	(1.025)	(1.097)	(1.296)	(1.696)
Ann1	-28.18***	-28.19***	-28.21***	-28.03***	-28.30***	-28.31***	-28.42***	-28.20***
	(3.221)	(3.213)	(3.203)	(3.204)	(3.218)	(3.205)	(3.215)	(3.211)
Ann2	0.908	0.869	0.876	0.814	0.988	0.977	1.061*	0.972
	(0.576)	(0.599)	(0.599)	(0.608)	(0.598)	(0.615)	(0.616)	(0.626)
Eligible		-0.475	-0.0605	-0.0505		-0.165	0.291	0.238
		(0.552)	(0.571)	(0.569)		(0.374)	(0.485)	(0.485)
Prev_purch.			-2.606***	-2.587***			-1.536*	-1.641*
			(0.936)	(0.930)			(0.860)	(0.854)
Multiple_purch.				-1.784*				-2.970**
				(0.941)				(1.251)
EoM	-2.098***	-2.096***	-2.052***	-2.033***	-2.126***	-2.126***	-2.123***	-2.101***
	(0.437)	(0.438)	(0.438)	(0.442)	(0.439)	(0.439)	(0.439)	(0.443)
Vix	2.704***	2.705***	2.704***	2.704***	2.702***	2.703***	2.701***	2.700***
	(0.465)	(0.465)	(0.465)	(0.465)	(0.465)	(0.464)	(0.464)	(0.464)
Term	-3.902***	-3.792***	-3.834***	-3.873***	-3.808***	-3.766***	-3.761***	-3.755***
	(1.000)	(1.079)	(1.075)	(1.068)	(0.995)	(1.068)	(1.061)	(1.057)
ST	-0.142	-0.531	-0.614	-0.574	-0.436	-0.580	-0.671	-0.658
	(0.438)	(0.413)	(0.422)	(0.413)	(0.286)	(0.409)	(0.420)	(0.413)
MT	-0.239	-0.385	-0.378	-0.347	-0.361	-0.416	-0.441	-0.444
	(0.281)	(0.281)	(0.279)	(0.273)	(0.246)	(0.275)	(0.279)	(0.270)
ULT	-0.162	-0.156	-0.157	-0.139	-0.148	-0.146	-0.138	-0.102
	(0.297)	(0.298)	(0.285)	(0.265)	(0.283)	(0.282)	(0.264)	(0.232)
Const.	4.456***	4.726***	4.862***	4.874***	4.642***	4.741***	4.826***	4.810***
	(1.283)	(1.093)	(1.086)	(1.083)	(1.234)	(1.080)	(1.071)	(1.066)
Obs.	25,146	25,146	25,146	25,146	25,146	25,146	25,146	25,146
R^2	0.019	0.019	0.019	0.019	0.018	0.018	0.019	0.019
Standard errors in parentheses			*** p<0.01, ** p<0.05, * p<0.1					

The table shows results of a panel regression to determine the impact of PSPP on bond prices, separated into four maturity buckets. Panel A includes a dummy taking the value of one if the specific bond is purchased on a given day. Panel B includes the dummy scaled by purchase volume. The set of controls includes the VIX, the spread between short- and long term bonds (denoted as "Term") and a dummy for end-of-month effects ("EoM"). To control for the impact of additional monetary policy decisions, we include dummies for the governing council meetings on December 3rd, 2015 ("Ann1"") and March 10th, 2016 ("Ann2"). Moreover, we add a dummy which controls for eligibility of the bonds from specification (2) onwards. Additionally, we include a dummy to control for the impact of a purchase of a particular bond on the previous day and a dummy to account for multiple purchases of the same bond on one day. Standard errors are clustered by bond. The sample period is from 09 March 2015 to 31 October 2016.

5 Asset Purchases and Bund Liquidity

Whether or not PSPP asset purchases possibly impair market functioning and affect liquidity conditions is an important question. If this is the case, greater transaction and hedging costs by the private sector may at least partially thwart some of the intended impact of the policies on the broader economy via the compression of yields. Our MTS order book data are perfectly suited to answer this question and should be of interest to academics, policymakers and market participants alike.

In general, the bid-ask spread is a good measure of the cost of immediacy in a market, while the available depth informs participants about the amount that can be immediately purchased without generating a large price move. Thus, we focus on these two key liquidity metrics in the following. We report the impact of PSPP purchase on bid-ask spreads in Table 9, and results on market depth are given in Table 10. The panel regression setup follows the one used in the previous section.

The results in Table 9 suggest that illiquidity of individual bonds, as measured by the bid-ask spread, tends to rise upon purchase of the securities. A EUR 100 million transaction is associated with a rise in bid-ask spreads between 4 and 8 basis points. These effects seem large in economic terms, but the significance is low in statistical terms. Controlling for eligible bonds increases the overall effect significantly. This implies that the difference in the bid-ask spread is less pronounced between purchased and non-purchased (but eligible) bonds than between purchased and non-eligible bonds. The result seems intuitive since the group of non-eligible bonds exhibits different characteristics than the group of eligible bonds. What is especially interesting is that accounting for those bonds which were purchased on the previous day decreases the overall effect on spreads. The reason might be that liquidity is especially strained in those bonds that are purchased on subsequent days.

Similar to the results for relative spreads, our results show that asset purchases lead to a drop in depth of the purchased securities relative to that of bonds not purchased on that day. Panel B shows that depth falls by between EUR 1.3 million and EUR 1.6 million, per EUR 100 million purchased. The results are significant across all specifications in Panel B of Table 10. This seems intuitive since especially large asset purchases should affect the depth available in the order book of the inter-dealer platform. However, in contrast to the results for spreads, the impact on depth seems to be more stable and not driven by bond-specific effects.

Table 9: Impact Asset Purchases on Bond Liquidity: Relative Bid-Ask Spreads

	Panel A: Purchases				**Panel B: Amounts**			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Ψ	-1.098	1.146	-1.197	-1.458	4.374	9.912*	7.780*	8.304
	(1.500)	(1.741)	(1.099)	(1.130)	(4.789)	(5.589)	(4.615)	(5.790)
Ann1	-7.759***	-7.943***	-7.914***	-8.172***	-7.758***	-8.251***	-8.127***	-8.065***
	(1.941)	(1.986)	(1.988)	(1.991)	(1.922)	(1.999)	(2.017)	(1.993)
Ann2	23.14**	22.42**	22.40**	22.49**	23.03**	22.39**	22.29**	22.27**
	(10.97)	(10.94)	(10.92)	(10.97)	(10.96)	(10.96)	(10.93)	(10.97)
Eligible		-8.743**	-9.338**	-9.352**		-9.663***	-10.17***	-10.19***
		(3.311)	(3.564)	(3.565)		(3.415)	(3.739)	(3.750)
Prev_purch.			3.755*	3.725*			1.723	1.695
			(2.026)	(2.021)			(1.915)	(1.921)
Multiple_purch.				2.583				-0.809
				(1.992)				(2.988)
EoM	-2.591***	-2.545***	-2.610***	-2.637***	-2.575***	-2.585***	-2.589***	-2.583***
	(0.762)	(0.752)	(0.754)	(0.758)	(0.766)	(0.763)	(0.760)	(0.760)
Vix	0.589**	0.607**	0.607**	0.608**	0.590**	0.606**	0.608**	0.608**
	(0.266)	(0.269)	(0.269)	(0.269)	(0.267)	(0.271)	(0.271)	(0.271)
Term	8.071**	10.09***	10.14***	10.20***	8.091**	10.54***	10.53***	10.53***
	(3.115)	(3.329)	(3.338)	(3.339)	(3.187)	(3.484)	(3.481)	(3.484)
ST	-12.92**	-20.08***	-19.96***	-20.02***	-11.88**	-20.35***	-20.24***	-20.24***
	(5.059)	(6.817)	(6.775)	(6.781)	(4.983)	(6.897)	(6.839)	(6.835)
MT	-10.34**	-13.03**	-13.04**	-13.08**	-10.13**	-13.35**	-13.32**	-13.32**
	(5.110)	(5.592)	(5.590)	(5.594)	(5.126)	(5.668)	(5.650)	(5.650)
ULT	35.84***	35.95***	35.95***	35.93***	35.83***	35.98***	35.97***	35.99***
	(1.127)	(1.127)	(1.128)	(1.128)	(1.123)	(1.123)	(1.123)	(1.122)
Const.	9.333*	14.33**	14.15**	14.13**	8.218	14.04**	13.95**	13.95**
	(5.242)	(5.915)	(5.861)	(5.855)	(5.346)	(5.935)	(5.875)	(5.879)
Obs.	25,223	25,223	25,223	25,223	25,223	25,223	25,223	25,223
R^2	0.154	0.157	0.157	0.157	0.154	0.158	0.158	0.158
Standard errors in parentheses			*** p<0.01, ** p<0.05, * p<0.1					

The table shows results of a panel regression to determine the impact of public sector asset purchases on bond market liquidity as measured by relative bid-ask spreads. As in the previous table 8 Panel A includes a dummy taking the value of one if the specific bond is purchased on a given day and Panel B includes the dummy scaled by purchase volume. The set of controls includes the VIX, the spread between short- and long term bonds (denoted as "Term") and a dummy for end-of-month effects ("EoM"). To control for the impact of additional monetary policy decisions, we include two dummies for the governing council meetings on December 3rd, 2015 ("Ann1") and March 10th, 2016 ("Ann2") from specification (2) onwards. Moreover, we add a dummy which controls for eligibility of the bonds. Additionally, we include a dummy to control for the impact of a purchase of a particular bond on the previous day as well as a dummy to account for purchases in 2016. Standard errors are clustered by bond. The sample period is from 09 March 2015 to 31 March 2016.

Table 10: Impact Asset Purchases on Bond Liquidity: Best Depth

	Panel A: Purchases				**Panel B: Amounts**			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Ψ	-0.229	-0.219	-0.110	-0.101	-1.328***	-1.359***	-1.336***	-1.629***
	(0.205)	(0.189)	(0.130)	(0.148)	(0.500)	(0.451)	(0.429)	(0.495)
Ann1	-1.435***	-1.436***	-1.437***	-1.428***	-1.393***	-1.390***	-1.391***	-1.426***
	(0.403)	(0.404)	(0.403)	(0.399)	(0.400)	(0.402)	(0.402)	(0.400)
Ann2	0.307	0.304	0.304	0.301	0.297	0.300	0.301	0.315
	(0.475)	(0.474)	(0.474)	(0.472)	(0.475)	(0.474)	(0.473)	(0.471)
Eligible		-0.0402	-0.0125	-0.0120		0.0535	0.0590	0.0672
		(0.298)	(0.294)	(0.293)		(0.295)	(0.285)	(0.287)
Prev_purch.			-0.175	-0.174			-0.0184	-0.00248
			(0.124)	(0.125)			(0.178)	(0.171)
Multiple_purch.				-0.0870				0.456
				(0.358)				(0.387)
EoM	-0.0607	-0.0605	-0.0574	-0.0565	-0.0537	-0.0537	-0.0536	-0.0571
	(0.104)	(0.104)	(0.104)	(0.104)	(0.104)	(0.104)	(0.104)	(0.104)
Vix	0.00888	0.00896	0.00893	0.00891	0.00925	0.00916	0.00914	0.00928
	(0.0216)	(0.0215)	(0.0216)	(0.0216)	(0.0216)	(0.0215)	(0.0216)	(0.0216)
Term	0.190	0.199	0.197	0.195	0.156	0.142	0.143	0.141
	(0.329)	(0.328)	(0.327)	(0.328)	(0.330)	(0.329)	(0.329)	(0.329)
ST	3.729***	3.696***	3.690***	3.692***	3.685***	3.732***	3.731***	3.729***
	(1.190)	(1.190)	(1.191)	(1.191)	(1.182)	(1.187)	(1.189)	(1.190)
MT	4.083***	4.070***	4.071***	4.072***	4.094***	4.112***	4.112***	4.112***
	(1.174)	(1.168)	(1.168)	(1.168)	(1.173)	(1.167)	(1.167)	(1.167)
ULT	-6.590***	-6.590***	-6.590***	-6.589***	-6.593***	-6.594***	-6.594***	-6.599***
	(1.127)	(1.127)	(1.128)	(1.128)	(1.123)	(1.123)	(1.123)	(1.122)
Const.	17.91***	17.93***	17.94***	17.94***	18.00***	17.97***	17.97***	17.97***
	(1.206)	(1.213)	(1.215)	(1.215)	(1.202)	(1.213)	(1.216)	(1.218)
Obs.	25,223	25,223	25,223	25,223	25,223	25,223	25,223	25,223
R^2	0.353	0.353	0.354	0.354	0.354	0.354	0.354	0.354
Standard errors in parentheses			*** p<0.01, ** p<0.05, * p<0.1					

The table shows results of a panel regression to determine the impact of public sector asset purchases on bond market liquidity as measured by depth at the top of the MTS order book. Panel A just includes a dummy taking the value of one if the specific bond is purchased on a given day. Panel B includes the dummy scaled by purchase volume. The set of controls includes the VIX, the spread between short- and long term bonds (denoted as "Term") and a dummy for end-of-month effects ("EoM"). To control for the impact of additional monetary policy decisions, we include two dummies for the governing council meetings on December 3rd, 2015 ("Ann1") and March 10th, 2016 ("Ann2") from specification (2) onwards. Moreover, we add a dummy which controls for eligibility of the bonds. Additionally, we include a dummy to control for the impact of a purchase of a particular bond on the previous day as well as a dummy to account for multiple purchases on one day. Standard errors are clustered by bond. The sample period is from 09 March 2015 to 31 October 2016.

6 Understanding the Mechanism

6.1 Price Impact Conditional on Market Conditions

The intra-day and daily price impact results suggest that public sector purchases have a persistent impact on bond prices. This price impact is not only a function of individual bond characteristics but may also vary with broader market conditions. Decisions on purchases follow a pre-defined quantitative target set by the ECB. There is limited scope for portfolio managers to "time" purchases depending on market conditions. In the following, we investigate (i) the impact of purchases conditional on market stress as captured by strained liquidity conditions, and (ii) whether the impact of purchases varies as a function of yields.

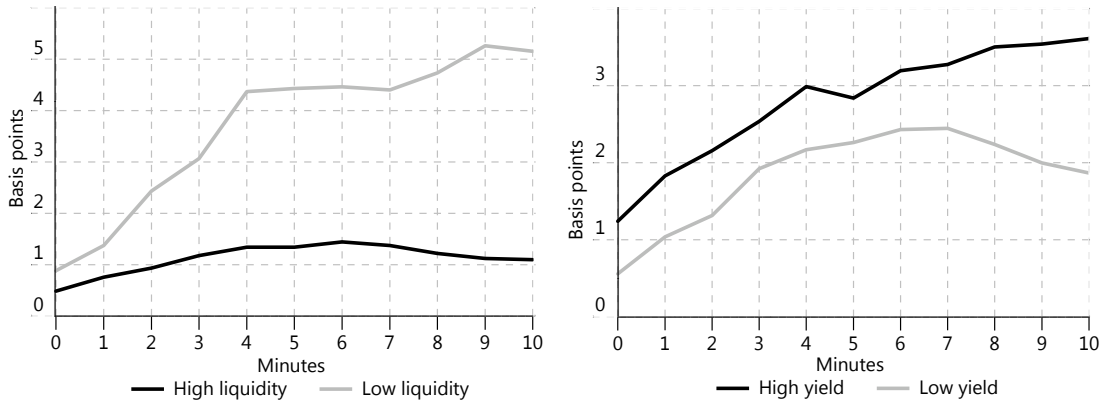
Table 11: Daily Price Impact Analysis: Financial Stress vs Calm Periods

Illiquid market		Purchase Dummy	Purchase Amount
	Coeff.	10.39***	8.217**
	s.e.	(2.141)	(3.218)
		+ *CONTROLS*	+ *CONTROLS*
	Obs	7,288	7,288
	R^2	0.047	0.043
Liquid market		Purchase Dummy	Purchase Amount
	Coeff.	1.292	6.239**
	s.e.	(1.085)	(2.547)
		+ *CONTROLS*	+ *CONTROLS*
	Obs	17,721	17,721
	R^2	0.012	0.013

This table investigates the impact of PSPP purchases on bond prices during different episodes of liquidity conditions. The setup is the same as in Table 8, but we run the panel regressions separately for periods of high and low relative bid ask spreads. To determine the cutoff, we calculate the time-series mean of relative bid-ask spreads for each bond and record days on which spreads are higher and lower than than their time-series average. To conserve space we only report coefficient estimates and standard errors on the purchase variables and not for the entire set of controls. The results are obtained based on the specification in column (4) of Table 8.

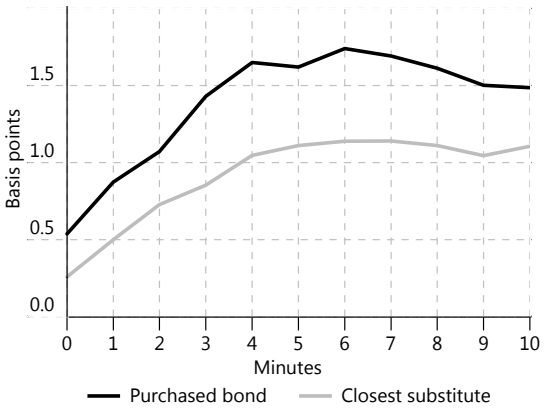
Price impact in liquid vs illiquid markets. We classify purchases depending on liquidity conditions measured by relative bid-ask spreads. For each bond purchase, the time-series mean one minute before the purchase is compared to the overall mean for that specific bond. If the bid–ask spread is above the time series mean, we classify the purchase as a purchase during an "illiquid market"; if it is below the mean, we classify it as a purchase during a "liquid market" regime.

Panel (a) of Figure 6 plots high-frequency price impacts for liquid and illiquid markets. The red line plots price impacts on illiquid days, while the blue depicts liquid days. The



(a) Price impact conditional on liquidity

(b) Price impact conditional on yield



(c) Comparison to closest substitute

Figure 6: This figure presents a variation of the intra-day price impact analysis of Figure 4. The upper-panel shows the average intra-day cumulative price impact of PSPP purchases of German government bonds depending on whether the purchase occurs in a "liquid" or "illiquid" market (measured via bid-ask spreads). The centre panel shows the price impact for periods of high vs low yields. The lower panel (upper panel) presents a comparison of the price impact of official sector purchases on the purchased bond to the price impact on the closest substitute (lower panel). The closest substitute is the bond with the closest maturity date to the purchased bond.

immediate price impact in an illiquid market is about 4 times larger than in liquid periods. And, the price impact further grows to 5 basis points after 10 minutes. By contrast, the price impact after 10 minutes is only about 1.3 basis points in times when markets are liquid. The figures highlight the fact that intra-day price impacts are higher and that the larger price impacts on low liquidity days appear to be highly persistent.

Panel regressions based on daily data confirm that asset purchases have a materially higher impact during stressed market conditions than in calm periods. Results of the daily panel regressions are reported in Table 11. The specification used in Table 11 is the same one as in column (4) of Table 8. Coefficients on the control variables are suppressed for ease of exposition and are similar to those reported in Table 8. We detect a price impact in an illiquid market of 10.4 basis points, compared to only 1.3 basis points in calm periods. For purchase amounts, the differences are less stark, but consistent with the intuition that price impacts are larger when liquidity is thin. It is also notable that the explanatory power for log bond price changes is substantially higher when markets are illiquid.

High vs. low yields. We further investigate whether the price impact of asset purchases is different in periods of high vs low bond yields. Panel (b) of Figure 6 shows the intra-day price impact across the two different regimes. Results obtained from the daily panel regressions are presented in Table 12.

The results suggest that the impact of asset purchases is materially larger in episodes of high yields. When yields are below their sample mean, the price impact of purchases is attenuated. In the daily panel regressions, the price impact of asset purchases becomes even insignificant in this case while it is highly economically and statistically significant in periods of high yields. These results tentatively suggest that during times of low demand for safe assets such as Bunds the impact of a large unilateral buyer is especially strong. This is supported by the evidence of the Bund Tantrum in May and June 2015 when Bund yields increased substantially. Another possible interpretation is that sustaining a price impact by asset purchases may become increasingly difficult as the program is successful in compressing yields.

6.2 Reaction of Close Substitutes

To shed further light on the mechanism by which asset purchases are transmitted across the yield curve, we repeat the previous analysis for purchased and closest substitute bonds. Purchased bonds are matched with non-purchased bonds based on remaining years to maturity (closest substitute). In general, matched samples are designed to isolate treatment effects, where the purchased bond is treated and the non-purchased bond is

Table 12: Daily Price Impact Analysis: High vs Low Yields

High yields		Purchase Dummy	Purchase Amount
	Coeff.	5.742***	17.38***
	s.e.	(1.325)	(3.937)
		$+ CONTROLS$	$+ CONTROLS$
	Obs	12,745	12,745
	R^2	0.024	0.024
Low yields		Purchase Dummy	Purchase Amount
	Coeff.	0.625	1.705
	s.e.	(1.493)	(2.193)
		$+ CONTROLS$	$+ CONTROLS$
	Obs	12,264	12,264
	R^2	0.005	0.005

The table investigates whether the impact of PSPP purchases on bond prices depends on the level of yields. The empirical setup is similar as in Table 8, but we now run the panel regressions separately for periods of high and low bond yields. To determine the cutoff, we calculate the time series mean of the yields for each bond and record days on which the yields are higher and lower than than their time-series average. Again, to conserve space we only report coefficient estimates and standard errors on the purchase variables and not for the entire set of control variables. The results are obtained based on the specification in column (4) of Table 8.

untreated. According to the portfolio balance channel, one would expect scarcity in one bond to spill over into securities that may be similar in terms of payoffs, credit risk, and maturity. This should lead closest substitute bonds to respond similarly, albeit perhaps to a lesser extent, than purchased bonds. An alternative interpretation is that the closest substitute impact represents the true impact on the yield curve. The difference between the price impact of purchased and substitute bonds could then be interpreted as a temporary and local price impact.

Panel (c) of Figure 6 plots high-frequency price impacts for purchased and closest substitute bonds. The black line plots price impacts on for purchased bonds and the blue line for closest substitute bonds. The price impact on closest substitute bonds is similar but less pronounced. This suggests that the local supply effect extends to bonds with similar cash-flows. This highlights the spillover effect for purchase programs, particularly when the supply is already relatively constrained.

Table 13: Daily Price Impact Analysis: Response of the Closest Substitute

Purchased bonds		Purchase Dummy	Purchase Amount
	Coeff.	3.074***	6.097***
	s.e.	(1.001)	(1.696)
		$+ CONTROLS$	$+ CONTROLS$
	Obs	25,146	25,146
	R^2	0.019	0.019
Closest substitutes		Purchase Dummy	Purchase Amount
	Coeff.	0.760	2.245
	s.e.	(1.571)	(1.685)
		$+ CONTROLS$	$+ CONTROLS$
	Obs	8,886	8,886
	R^2	0.017	0.017

This table compares the impact of PSPP purchases on the purchased bond to that on its closest substitute. The closest substitute is determined as described in the text. To conserve space we only report coefficients and standard errors on the purchase variables and not the entire set of control variables. The results are obtained based on the specification in column (4) of Table 8. For ease of comparison, the results of specification (4) of Table 8 are reported again in the upper panel.

Table 13 reports coefficients on purchased and substitute bonds. The purchased bonds results repeat those reported for specification (4) of Table 8. Closest substitute bonds respond positively but to a lesser extent than the group of all bonds at the daily frequency. The coefficients on purchased bonds is statistically zero for closest substitute bonds. For purchase amounts, the bond price of the closest substitute increases by 2.2 basis points. While economically relevant, the impact is less than half of the impact of purchased relative to all bonds.

7 Conclusion

This paper studies the impact of central bank asset purchases on prices and liquidity based on a transaction-level perspective. The series of exogenous shocks to bond supply induced by the central bank in individual securities provides a natural laboratory to study the relevance of scarcity effects for bond pricing. Thus, our results not only speak to the relevance of term structure theories emphasizing the role of frictions, they also shed new

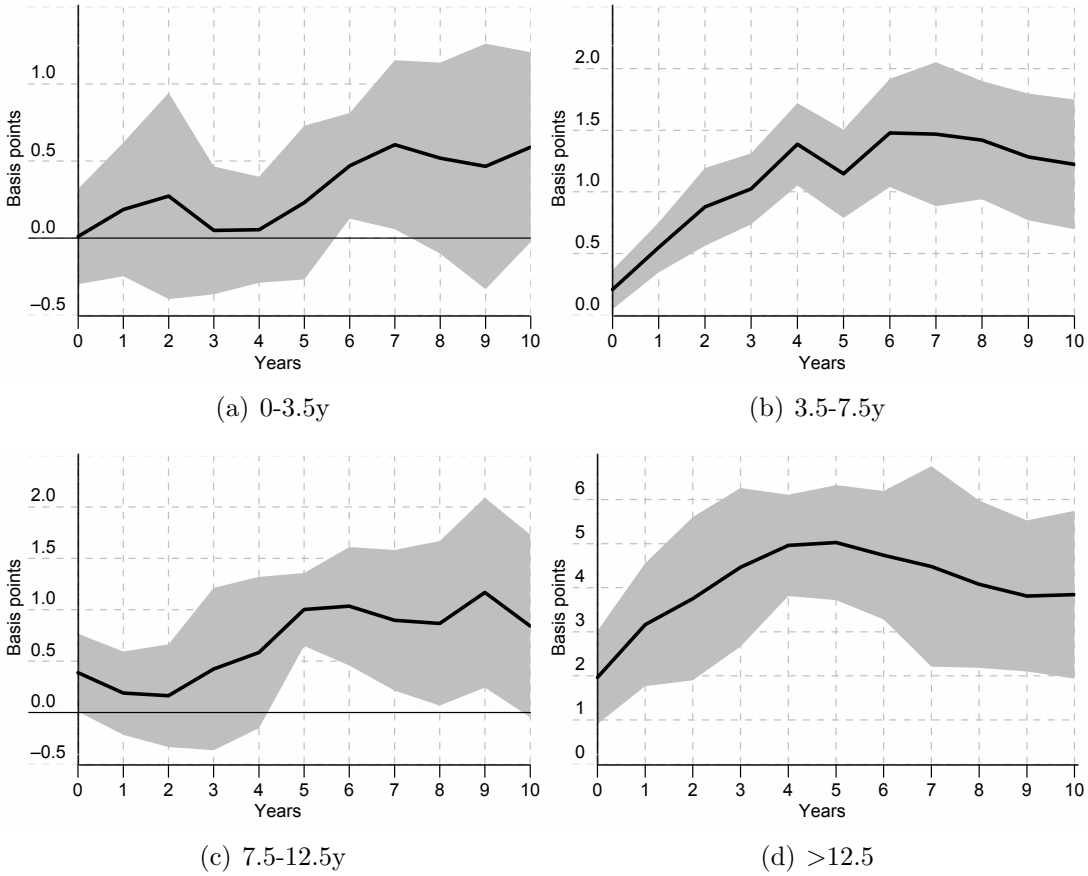
light on the transmission channels of quantitative easing (QE) policies.

We show that the asset purchases of the Eurosystem have a direct (high-frequency) impact on bond prices in the inter-dealer market. A public sector purchase leads to an average price impact of 1.6 basis points after about five minutes. As non-transacting dealers gradually learn about the purchase, they subsequently adjust quotes and the market settles on new equilibrium prices. All in all, our results provide evidence that QE policies do not just work via a signalling channel, but that scarcity effects play an important role, too.

We further investigate the impact of PSPP on market functioning and liquidity conditions in fixed income markets. Our focus is on the impact on relative bid-ask spreads and order book depth. Our results indicate that liquidity has deteriorated throughout the purchase program and likely also as a result of the purchase program.

The impact of asset purchases on bond prices evolves over time. We find that it is particularly in market stress episodes, when bond prices respond the strongest to central bank order flow. These results point to an asymmetric impact of quantitative easing that depends on the level of market stress. Moreover, the price impact of asset purchases is significantly larger in periods of high yields, highlighting the state-dependence of the price impact of purchases. These results further suggest that a timing of purchases conditional upon market conditions could potentially be beneficial from an implementation perspective of quantitative easing policies.

A Appendix



(a) 0-3.5y

(b) 3.5-7.5y

(c) 7.5-12.5y

(d) >12.5

Figure A.1: This figure shows the average intra-day cumulative price impact of PSPP purchases of German government bonds for different maturity segments of the yield curve. The horizontal axis indicates the minutes elapsed after the public sector purchase occurring at $t = 0$. The estimation of price impact is obtained based on a bi-variate VAR of (log) bond returns and public sector order flow in the spirit of Hasbrouck (1991). The estimation is performed at the level of individual bonds. The cumulated price impacts are aggregated across bonds for each step by means of a cross-sectional regression (of the price impact at the indicated lag) onto a constant. The gray lines indicate 95% confidence bands obtained from the cross-sectional regression.

References

Altavilla, C., G. Carboni, and R. Motto (2015). Asset purchase programmes and financial markets: Lessons from the euro area. ECB Working paper 1864.

Bauer, M. D. and G. D. Rudebusch (2014). The signaling channel for federal reserve bond purchases. *International Journal of Central Banking 10*(3).

Bech, M., A. Illes, U. Lewrick, and A. Schrimpf (2016, March). Hanging up the phone - electronic trading in fixed income markets and its implications. *BIS Quarterly Review*, 79–94.

Borio, C. and A. Zabai (2016). Unconventional monetary policies: a re-appraisal. BIS Working Paper.

Breedon, F. and P. Turner (2016). On the transactions costs of Quantitative Easing. BIS working paper, No. 571.

CGFS (2014). Market-making and proprietary trading: Industry trends, drivers and policy implications. Committee on the Global Financial System. Bank for International Settlements.

CGFS (2016). Fixed income market liquidity. Committee on the Global Financial System. Bank for International Settlements.

Chodorow-Reich, G. (2014, Spring). Effects of Unconventional Monetary Policy on Financial Institutions. *Brookings Papers on Economic Activity*, 155–204.

Christensen, J. and J. Gillan (2016). Does Quantitative Easing affect market liquidity. Working Paper 2013-26, Federal Reserve Bank of San Francisco.

Christensen, J. H. E. and G. D. Rudebusch (2012). The response of interest rates to US and UK Quantitative Easing. *The Economic Journal 122*(564), F385–F414.

D'Amico, S., R. Fan, and Y. Kitsul (2014). The scarcity value of treasury collateral: Repo market effects of security-specific supply and demand factors. Federal Reserve Board working paper 2014-60.

D'Amico, S. and T. B. King (2013). Flow and Stock Effects of Large-Scale Treasury Purchases: Evidence on the Importance of Local Supply. *Journal of Financial Economics 108*(2), 425–448.

Dunne, P. G., H. Hau, and M. J. Moore (2014). Dealer intermediation between markets. *Journal of the European Economic Association 13*, 770–804.

Eser, F. and B. Schwaab (2016). Evaluating the impact of unconventional monetary policy measures: Empirical evidence from the ECB's securities markets programme. *Journal of Financial Economics 119*, 147–167.

Fratzscher, M., M. L. Duca, and R. Straub (2012). A global monetary tsunami? on the spillovers of US Quantitative Easing. CEPR Discussion Paper 9195, Centre for Economic Policy Research.

Gagnon, J., M. Raskin, J. Remache, and B. Sack (2011, March). The financial market effects of the Federal Reserve's large-scale asset purchases. *International Journal of Central Banking 7*(1), 3–43.

Gilchrist, S. and E. Zakrajsek (2013). The impact of the Federal Reserve's large-scale asset purchase programs on corporate credit risk. *Journal of Money, Credit and Banking 45*(2), 29–57.

Greenwood, R. and D. Vayanos (2010, Spring). Price Pressure in the Government Bond Market. *American Economic Review: Papers and Proceedings*, 585–590.

Greenwood, R. and D. Vayanos (2014). Bond Supply and Excess Returns. *Review of Financial Studies 27*, 663–712.

Hasbrouck, J. (1991). Measuring the Information Content of Stock Trades. *Journal of Finance 46*(1), 179–207.

Hattori, M., A. Schrimpf, and V. Sushko (2016). The Response of Tail Risk Perceptions to Unconventional Monetary Policy. *American Economic Journal: Macroeconomics 8*, 11–136.

Hendershott, T. and A. Madhavan (2015). Click or call? auction versus search in the over-the-counter market. *The Journal of Finance 70*(1), 419–447.

Joyce, M. A. and M. Tong (2012). QE and the gilt market: A disaggregated analysis. *The Economic Journal 122*(564), F348–F384.

Joyce, M. A. S., A. Lasaosa, I. Stevens, and M. Tong (2011). The financial market impact of Quantitative Easing in the United Kingdom. *International Journal of Central Banking 7*(3), 113–161.

Kandrac, J. (2014). The costs of Quantitative Easing: Liquidity and market functioning effects of Federal Reserve MBS purchases. Working Paper.

Kandrac, J. and B. Schlusche (2013). Flow effects of large-scale asset purchases. *Economics Letters 121*(2), 330–335.

Krishnamurthy, A., S. Nagel, and A. Vissing-Jorgensen (2015). ECB policies involving government bond purchases: Impacts and channels. Working paper.

Krishnamurthy, A. and A. Vissing-Jorgensen (2011). The effects of Quantitative Easing on interest rates: Channels and implications for policy. NBER Working Papers 17555, National Bureau of Economic Research, Inc.

Krishnamurthy, A. and A. Vissing-Jorgensen (2012). The aggregate demand for treasury debt. *Journal of Political Economy 120*(2), 233 – 267.

Krishnamurthy, A. and A. Vissing-Jorgensen (2013). The Ins and Outs of LSAPs. In *Kansas City Federal Reserve Symposium on Global Dimensions of Unconventional Monetary Policy*.

MC (2016). Electronic trading in fixed income markets. Markets Commitee. Bank for International Settlements.

McLaren, N., R. Banerjee, and D. Latto (2014). Using Changes in Auction Maturity Sectors to Help Identify the Impact of QE on the Yield Curve. *Economic Journal 124*, 453–479.

Meaning, J. and F. Zhu (2011, December). The impact of recent central bank asset purchase programmes. *BIS Quarterly Review*.

Meaning, J. and F. Zhu (2012, March). The impact of Federal Reserve asset purchase programmes: Another twist. *BIS Quarterly Review*.

Pelizzon, L., M. Subrahmanyam, D. Tomio, and J. Uno (2016). Sovereign credit risk, liquidity, and ECB intervention. *Journal of Financial Economics 122*, 86–115.

Riordan, R. and A. Schrimpf (2015, September). Volatility and Evaporating Liquidity During the Bund Tantrum. *BIS Quarterly Review*, 11–12.

Schestag, R., P. Schuster, and M. Uhrig-Homburg (2015). Measuring liquidity in bond markets. *Review of Financial Studies, forthcoming*.

Song, Z. and H. Zhu (2016). QE auctions of treasury bonds. *Available at SSRN 2756674*.

Woodford, M. (2012). Methods of policy accommodation at the interest-rate lower bound. In *Jackson Hole Symposium, August, Federal Reserve Bank of Kansas City.*

Wright, J. H. (2012). What does monetary policy do to long-term interest rates at the zero lower bound? *The Economic Journal 122*(564), F447–F466.