Dealer balance sheets and bidding behavior in the Bank of England's QE reverse auctions

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September 13, 2024

Abstract

We study dealers' bidding behavior in the Bank of England's quantitative easing (QE) reverse auctions. Using a novel data set on both accepted and rejected offers together with an equilibrium model of bidding behavior, we estimate dealers' valuations of securities offered to the Bank of England. We also recover the rents accruing to dealers from participating in the auctions as opposed to liquidating gilts in the secondary market, whereby possibly causing prices to change. These rents or so-called "liquidity benefits" are largest in the early phases of QE implemented during Global Financial Crisis, suggesting that QE may be particularly effective in restoring smooth market functioning when market participants are facing large liquidity shocks. Finally, we document that dealers' valuations vary significantly with the amount of interest rate risk acquired in the secondary gilt market before the auction and with dealers' regulatory capital.

Keywords: quantitative easing, reverse auctions, dealer balance sheets, structural estimation.

JEL classification: E52, D44, C57.

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1 Introduction

During the global financial crisis and the covid pandemic, many central banks engaged in unconventional monetary policy operations in the form of outright asset purchases—commonly known as quantitative easing (QE). The primary objective of these operations was to provide further monetary accommodation at times when nominal interest rates hit the zero lower bound. But central banks have also employed asset purchases to address temporary dysfunction in government bond markets, such as during the Covid-induced turmoil in the U.S. Treasury market in March 2020 (Vissing-Jorgensen (2020)) or, in response to a sudden increase in long-dated U.K. government bond yields in September 2022 (Bank of England (2022), Pinter (2022)). By arresting fire-sale dynamics, these targeted purchases helped to restore orderly conditions in safe-asset markets and thus contributed to financial stability more broadly (Duffie (2023), Vissing-Jorgensen (2020), Hauser (2022)).

Most central banks implement QE through reverse auctions where primary dealers compete to sell eligible assets to the central bank. In the United Kingdom (U.K.), the Bank of England (BoE) purchased over £800 billion worth of U.K. government bonds (so-called gilts) between 2009 and 2022, amounting to around one-third of all gilts in issue. Despite the size and scope of these operations, research studying the mechanics of the reverse auctions, dealers' bidding behavior, and auction outcomes is relatively scarce.

In this paper, we attempt to bridge this gap and make several novel contributions to the literature. First, we collect a proprietary data set recording both accepted and rejected offers submitted by primary dealers in the BoE's reverse auctions. This novel data set allows us to estimate an equilibrium model of bidding in reverse auctions and thus recover dealers' willingness-to-sell gilts to the BoE that rationalize the observed offers, as well as the usual private-information rents accruing to dealers by participating in these auctions and behaving strategically. Second, we document that these rents or "liquidity benefits" of running the auctions have been largest during times of market dysfunction, indicating that the BOE's auctions have been effective as a backstop for secondary market liquidity. Finally, we show that dealers' willingness-to-sell varies with dealers' balance sheet constraints, originating from the regulatory capital framework and from internal management of interest rate risk.

Specifically, our novel proprietary data set contains offers submitted by primary dealers in the 352 reverse gilt auctions run by the BoE between March 2009 and March 2017. In contrast to other papers in the literature, we have information on both offers that were accepted and those that were rejected in each auction. Armed with this novel granular data, we first estimate dealers' private valuations or their willingness-to-sell, adapting the methods developed in Hortaçsu and McAdams (2010), Kastl (2011), and Hortaçsu and Kastl (2012). Our model is standard in the literature on auctions while at the same time respecting institutional details about the BoE's gilt QE auctions.

Following Kastl (2012), we assume that bids have to be submitted as a collection of price-quantity pairs, defining the demand curve for central bank reserves as a step-function, and our model allows for different securities to be sold to the auctioneer. To estimate dealers' willingness-to-sell, the basic idea is to use the variation in bids to infer the distribution of the residual supplies a bidder is facing. Assuming primary dealers participating in the QE auctions rationally anticipate bidding against this distribution, and that they submit bids that maximize their expected profits, one can then estimate the marginal willingness-to-sell a given security that rationalizes the observed bid. This inversion technique is by now standard in empirical analysis of auctions, but our application to the QE reverse auctions is novel.

After estimating dealers' valuations, we can then recover rents or liquidity benefits accruing to the dealers from participating in the auctions as opposed to liquidating gilts in the secondary market. We document that liquidity benefits are largest in the early phases of QE implemented during global financial crisis, consistent with previous work suggesting that the so-called liquidity channel is more powerful during times of market turmoil (Bailey et al. (2020), Vissing-Jorgensen (2020)). Hence, QE may be particularly effective in restoring smooth market functioning when market participants are facing large liquidity shocks and simultaneously sell large quantities of safe assets, lending support to a recent theory by Eisenbach and Phelan (2022).

Next, we study the determinants of dealers' bidding behavior, focusing on constraints that affect dealers' willingness to hold interest rate risk on their balance sheets. These constraints stem from dealers', internal risk-management constraints such as position limits, Value-at-Risk limits, and risk-factor exposure limits (Amihud and Mendelson (1980), Duffie et al. (2023), Anderson et al. (2023)), funding constraints (Brunnermeier and Pedersen (2008), He and Krishnamurthy (2013)), regulatory constraints, such as capital and liquidity requirements (Adrian et al. (2017), Duffie (2018)), and restrictions on proprietary trading (Iercosan et al. (2021)).

To understand how these constraints affect dealers bidding behavior, we collect audit-trail transaction-level data for individual gilts in the secondary market, enabling us to estimate how much interest rate risk dealers have accumulated ahead of each auction. Our results suggest that dealers use the BoE's auctions as an exit strategy for unwanted or strategically accumulated gilt positions: The willingness-to-sell is higher if a dealer has increased her interest rate exposure ahead of the auction, and is lower if a dealer has sold interest rate risk instead.

Balance sheet constraints originating from regulation can also affect dealers' bidding behavior. Specifically, following an exemption rule implemented in 2016, U.K. banks can improve their leverage ratios—the minimum amount of equity capital banks must hold regardless of the riskiness of their assets—by exchanging gilts for central bank reserves. Consistent with these regulatory incentives, our results suggest that dealers actively use QE auctions to meet their leverage ratio requirements.

Finally, we compute the cost of running the auctions incurred by the BOE. The average cost is around 0.4 bps, which is less than the average bid-ask spread in the gilt market. Clearly any such measure of the costs of QE auctions should be put in the context of the much broader macroeconomic benefits of the policy—that is, stimulating economic activity and achieving the BoE's inflation target.

The remainder of this paper is organized as follows. Section 2 explains the design of the BoE's gilt QE auctions. Section 3 describes the data employed in the paper and Section 4 introduces our structural auction model. Section 5 studies liquidity benefits dealers obtain when participating in the auctions. Section 6 estimates the role played by inventory risk and regulatory constraints in explaining dealers' bidding behavior. Section 7 reports the cost of running the auctions incurred by the BOE. Section 8 concludes.

Related literature. Our paper is most closely related to the nascent literature examining the design and cost of QE operations through the lens of auction data. Song and Zhu (2018) study dealer profits in Treasury QE auctions in the U.S. between November 2010 and September 2011. In a related paper, Bonaldi et al. (2015) assess dealer profits and efficiency in the Federal Reserve Board's QE auctions of Treasury and mortgage-backed securities. Breedon (2018) computes the "round-trip" costs of issuing gilts in the primary market and purchasing them via QE reverse auctions. Finally, An and Zhaogang (2022) document that in the Fed's agency MBS auctions, dealers charge a higher price to the Fed compared to other customers and they attribute this finding dealers' market power. These papers use publicly available auction outcomes and market prices. Compared to these papers, the advantage of our data is that it records both accepted and rejected offers, allowing us to estimate dealers' private willingness-to-sell.

In addition, this paper is related to research providing evidence for the liquidity channel in transmission of QE (Vissing-Jorgensen and Krishnamurthy (2011), Eser and Schwaab (2016), Pooter et al. (2018), Vissing-Jorgensen (2020), Grimaldi et al. (2021), Christensen and Gillan (2022), Boneva et al. (2022)). While our econometric approach is different from the empirical approaches in these papers, we also find that central bank asset purchases improve liquidity conditions in secondary markets, in particular in times of market stress.[1]

More broadly, the paper is also related to the recent literature studying the effects of central bank interventions on the functioning of government bond markets. Duffie (2023) and Duffie and Keane (2023) discuss the costs and benefits of market function interventions and argue that well-designed official sector purchases would provide a liquidity backstop in times of stress, improving primary market demand for Treasuries and reducing the cost of debt to the government. Eisenbach and Phelan (2022) show theoretically that when dealers' balance sheet capacity is constrained asset purchases are a particularly effective tool for restoring orderly functioning in safe asset markets. Vissing-Jorgensen (2020) documents that the Federal Reserve's purchases of Treasury securities reduced Treasury yields during

[1] We focus on actual asset purchases and so our approach cannot distinguish between alternative transmission mechanisms of QE, such as local supply, duration, or signaling (Vissing-Jorgensen and Krishnamurthy (2011), Busetto et al. (2022)) , some of which operate at the time of the announcement of the operations rather than at the time of implementation.

the dash-for-cash episode in March 2020. Our estimation shows that the liquidity benefit dealers obtain from the reverse auctions is sizable and so the BoE's QE purchases may have played an important role in helping to alleviate market dysfunction and arrest fire sale dynamics in times of market stress.

Our paper is also related to the literature studying interest rate risk management at dealers and banks more broadly. At the bank level, Drechsler et al. (2017) and Drechsler et al. (2022) show that banks are exposed to interest rate risk through their deposit franchise, which increases in value when interest rates rise, thereby naturally hedging banks' holdings of long-term fixed rate assets, which tend to depreciate with rising interest rates. Drechsler et al. (forthcoming) observe that the deposit franchise is only valuable if the deposits stay inside the bank when interest rates rise and develop a theory of optimal management of the associated liquidity risk. English et al. (2018) show that bank stock prices decline after unexpected increases in the level and slope of the yield curve, suggesting that bank equity is somewhat sensitive to interest rates, although, as Drechsler et al. (2022) point out, this sensitivity is an order of magnitude smaller than that implied by banks mismatch between the maturity of their assets and liabilities.

Primary dealers typically operate in a different way from commercial banks in that they fund their inventory in short-term wholesale funding markets and manage the associated inventory risk by imposing internal risk limits, such as position limits, risk-factor-exposure limits, and Value-at-Risk limits (Duffie et al. (2023), Anderson et al. (2023)). Using high-frequency data on trading-book profits at major U.S. banks—most of which are also U.S. primary dealers—-Iercosan et al. (2021) show that these banks have, on average, economically small exposures to interest rate risk in their trading books. Our results are consistent with this finding – U.K. primary dealers seem reluctant to accumulate large interest rate risk exposures in the trading book and hence offload the gilts more aggressively in the reverse auction when they do acquire a large inventory prior to the auction.

Furthermore, the paper is related to the literature on the effects of capital regulation on dealer intermediation in Treasury markets. Duffie (2018) argues that the leverage ratio requirements for large banks may reduce their willingness and ability to intermediate in markets for safe assets. Consistent with these predictions, Favara et al. (2022) find significant negative effects of the leverage ratio requirements on banks' participation in the U.S. Treasury market. Breckenfelder and Ivashina (2023) document that following the introduction of the leverage ratio in Europe the liquidity of corporate bonds declines when dealer banks move closer to their leverage ratio requirement. However, Bicu-Lieb et al. (2020) study the effect of the leverage ratio requirement on the secondary market for U.K. gilts and show that while market liquidity generally deteriorated with the introduction of this requirement, they do not find a conclusive, causal link between the two. We contribute to this literature by showing that regulatory constraints affect dealers' bidding behavior in QE auctions.

Finally, this paper is also related to the literature studying the cost and efficiency of primary auctions of government securities (Hortaçsu and McAdams (2010), Kastl (2011), Hortaçsu and Kastl (2012), Hortaçsu et al. (2018), Han et al. (2007), Kang and Puller (2008)). These papers focus mostly on comparing auction formats across various countries and argue that the data do not show that one format would dominate the others. In this paper, we borrow from the methods developed in those papers to estimate dealers' willingness-to-sell a gilt to the Bank of England and we use these estimates to quantify rents accruing to QE participants.

2 Institutional background

This section introduces the auction protocol used by the BoE to purchase gilts and explains how trading takes place in the secondary market for gilts. This information is used in Section 4 to setup a structural model that is consistent with these facts.

2.1 Quantitative easing in the United Kingdom

After the policy rate in the U.K. was lowered to 0.5 percent in early 2009, the Monetary Policy Committee (MPC) of the BoE announced outright purchases of U.K. government bonds (gilts) on March 5, 2009. The initial stock of purchases amounted to £75 billion but was increased to £200 billion shortly thereafter.[2] In 2011 and 2012, the purchases were

[2] Between different rounds of QE, the stock of QE purchases was maintained by reinvesting the principal amount of maturing gilts.

further extended to £300 and £375 billion, respectively. Following the U.K.'s European Union membership referendum in July 2016, the MPC announced a further round of QE purchases worth £60 billion. In 2020, the BoE's MPC announced to purchase an additional £450 billion of government bonds and sterling non-financial investment-grade corporate bonds to tackle the economic outfall of the covid pandemic. The stock of gilts held by the BoE peaked at £875 billion at end of 2021, amounting to approximately one-third of annual UK GDP. In September 2022, the BoE announced to reduce the stock of gilts held by the APF. Besides for monetary policy purposes, the BoE also used QE to safeguard financial stability by conducting temporary purchases of long-dated UK government bonds in September and October 2022 to restore orderly market conditions after a sudden repricing had occurred.

The asset purchases were financed by creation of central bank reserves and formally carried out by the Bank of England's Asset Purchase Facility Fund Limited which is a subsidiary of the BoE. The Asset Purchase Facility is fully indemnified by HM Treasury, the U.K. finance ministry, against losses associated with its QE operations and any profits from the Asset Purchase Facility portfolio are returned to the Treasury.

2.2 The design of reverse QE auctions in the United Kingdom

To implement QE, the BoE uses a multi-object, multi-unit, discriminatory price reverse auction format.[3] Eligible participants include the participants in the BoE's gilt-purchase open market operations and the Gilt-Edged Market Makers (primary dealers) as listed on the website of the U.K.'s Debt Management Office. In each auction, participants are allowed to submit an unlimited number of offers containing price, quantity, and the gilt identifier.[4]

[3] See also the most recent market notice for details on the design of the reverse QE auctions, available at: `https://www.bankofengland.co.uk/markets/market-notices/2019/asset-purchase-facility-gilt-purchases-june-2019`.

[4] In addition to the competitive auctions, some participants are eligible to sell gilts in a non-competitive auction at the average accepted price determined in the competitive auction. Dealers only submitted non-competitive bids during QE1, and only 1 percent of the purchased amount is allocated to non-competitive bids (Joyce and Tong (2012)). There are several reasons for why participating dealers preferred to submit their bids in the competitive auction: (i) participation in the competitive auction is operationally easier, (ii) non-competitive bids need to be submitted by noon on the auction day, leaving dealers exposed to interest rate risk until around the price is announced at around 14.50, and (iii) in case the gilt a dealer placed a non-competitive bid for is not allocated in the competitive auction, the non-competitive bid will be cancelled.

The auctions are conducted on a weekly basis and are scheduled from 2:15 to 2:45 p.m. The BoE runs separate auctions for different maturity sectors and these auctions take place on different days. Initially, the BoE ran only two auctions per week, one for maturities between 5 and 10 years, and one for maturities between 10 to 25 years. As of August 6, 2009, the number of maturity sectors was expanded to include long-term gilts (over 25 years of residual maturity), and the maturity sectors were further modified in February 2012 (Table 1).

In the week ahead of each auction, the BoE publishes a list of eligible gilts. In general, the purchases exclude gilts with residual maturity less than three years, gilts of which the BoE already holds more than 70 percent of free float, index-linked gilts, and gilts with an issue size of £4 billion or less. Gilts that are newly issued by the Debt Management Office in the week preceding the auction or those that will be re-opened by the Debt Management Office either one week before or after the auction are also excluded.

Figure 1 graphically illustrates how the auctions are run in practice. On auction days, dealers submit their offers to sell eligible gilts to the BoE between 2:15 to 2:45 p.m.. After the auction is closed, the received offers are ranked according to the spread between the offered yield and the secondary market yield prevailing at the auction close. The BoE accepts the most attractive offers until the announced volume has been filled. Successful auction participants are notified privately and receive their offer price, consistent with the discriminatory price protocol. After the close of each auction, the BoE publishes aggregate auction results including quantities offered and allocated. Information on individual offers is not made public.

Before and during each auction, the BoE closely monitors the developments in the secondary market and reserves the right to exclude a gilt from the auction should unusual price developments occur.[5]

To ensure a specific offer is accepted, dealers therefore prefer to submit a competitive bid at a low price.

[5]Breedon (2018) provides an example of price manipulation in an eligible gilt that occurred on October 10, 2011, leading to a fining of the responsible trader by the U.K.'s Financial Conduct Authority.

2.3 The secondary market for gilts

The U.K. primary dealers play a vital role in the secondary gilt market. They are required to provide liquidity to market participants by quoting bid and ask prices on a continuous basis in all market conditions. In return, they are eligible to participate in the U.K. primary auctions and related operations run by the U.K. Debt Management Office. The vast majority of trading in the secondary gilt market is carried out over the counter (OTC) and only a small amount occurs on the London Stock Exchange.[6] The number of primary dealers varies during our sample period, as some firms resigned their primary dealer status, while new firms acquired it. In total, there were 22 different primary dealers active during our sample period (Table 3).

3 Data

This section introduces the novel, granular data set we use to analyse bidding behavior in the BoE‘s QE auctions.

3.1 Auction data

Our auction data set covers 352 QE auctions that took place between March 2009 and March 2017. The majority of these purchases are concentrated in four distinct phases, known as QE1-QE4 (Table 2). But auctions also took place between these QE programs in order to reinvest the proceeds from maturing gilt holdings. A unique feature of our data is that it records detailed information about each individual bid submitted during the auctions. This includes the identity of the dealer, the gilt to be offered to the BoE, the offer yield and quantity, and the allocated amount (which can be zero). This information is not only available for accepted offers, but for all offers that were submitted into the auction. For each auction, we also have data for the gilt yields that prevailed in the secondary market at the close of the auction (2:45 p.m.) that is used by BoE staff in the allocation process.

[6] Benos and Zikes (2018) and Bicu-Lieb et al. (2020) provide a detailed description and analysis of the U.K. gilt market structure.

Our data includes both offers placed by dealers on their own behalf as well as offers placed on behalf of their clients. Because clients are likely to follow a different offering strategy compared with dealers' own accounts, client offers are removed from our data prior to analysis. Specifically, we exclude offers where the offer amount exceeds £100 million or offers placed at a speculative price that exceeds the prevailing market price by a sizable margin.[7] In total, this procedure identifies around 4% of all offers as offers placed on behalf of clients.

Table 4 reports descriptive statistics for the auction data at the aggregate level, broken down by QE phase and residual maturity. The average number of eligible gilts per auction is 8, but some auctions during QE4 run with as little as 2 gilts while others included more than 10 eligible different gilts. The average number of participating dealers is 16, with a minimum of 14 during QE1 and a maximum of 18 during QE2. On average, the amount offered per auction is £2389 million and the BoE purchased on average £893 million per auction, indicating that the auctions were well covered.[8] Measured by the amount offered or amount purchased, auctions held during QE1 were larger compared to later QE phases, in particular for the medium and long maturity buckets.

Figures 2 and 3 report descriptive statistics by dealer and gilt. The average amount offered per dealer and gilt is £57 million, similar to the average trade size in the UK gilt market (Belsham et al. (2017)). The average amount accepted by dealer and gilt is £40 million. The largest amounts offered and accepted are observed during QE1 that was implemented in 2009 when secondary market functioning was poor. Also, the average amount offered is smaller in the large maturity bucket compared to the short- or medium maturity bucket. Offering a long-dated gilt exposes dealers to more interest rate risk, explaining why the amount offered of these gilts is around £20 million smaller compared to gilts in the short- or medium maturity bucket.

[7] To determine speculative offer yields, we compute the distribution of offer yields relative to the market yields at auction close and remove the offers below the 1st percentile. This is done separately for the different QE phases and maturity buckets. The thresholds for removing client offers have been provided to us by the BoE's QE desk and are informed by regular conversations with auction participants.

[8] One exception was an uncovered auction in August 2016 with a shortfall of £52 million.

3.2 Transaction records from the U.K. secondary gilt market

Our secondary market transaction data are obtained from the ZEN database maintained by the U.K. Financial Conduct Authority for the period from August 2011 until March 2017, covering the QE2, QE3, reinvestment, and QE4 phases. In total, there were 61 different conventional gilts traded during our sample period, including gilts issued prior to the beginning of the sample period as well as gilts issued during the sample period. Each transaction record contains the trading account of the reporting party, transaction date and time, gilt identifier, execution price, size of the transaction, buyer/seller flag, reporting party name and frequently, but not always, the identity of the counterparty. Large dealer banks typically have multiple trading accounts corresponding to the different functions these banks perform. For the purposes of this paper, we are only interested in the activities associated with market making and hence only retain the trading accounts used for this purpose. To identify the market-making accounts, we follow the methodology in Kondor and Pinter (2019).[9]

Once having identified dealers' market making accounts, we aggregate notional volumes bought and sold across different accounts to construct measures of trading activity for each dealer and gilt. Notional volumes bought and sold are then accumulated over 2.5 days preceding of each auction.[10] To translate the notional volumes traded into interest rate risk, the notional volumes bought and sold are multiplied by a gilt's duration (DV01), which measures the change in the value of a bond with a 1 basis point change in its yield.[11]

Table 5 reports descriptive statistics for both interest rate risk and traded volumes. On average, we find that the trading activity larger for gilts that have been offered or purchased compared to those that are eligible or ineligible.

[9]Kondor and Pinter (2019) develop a fixed-point algorithm and show that it successfully identifies the market-making accounts of the primary dealers in the gilt market. For robustness, we apply an alternative procedure that identifies market-making accounts using a narrative procedure by selecting accounts that exhibit a large, two-way trading activity together with a name indicating market-making activity. The correlation between the traded volume computed using either method is around 95 percent and all regression results are robust to identifying market-making accounts using the alternative method.

[10]Specifically, traded volumes is accumulated on the auction day itself until the start of the auction at 2:15 p.m. and on the 2 days preceding each auction. Because auctions for the different maturity buckets are held weekly, 2.5 days is exactly in the middle between two subsequent auctions. Using a window over 2.5 days also ensures that a sufficient number of transactions is observed.

[11]Online Appendix A describes the construction of these measures of interest rate risk in more detail.

3.3 U.K. dealer balance sheet data

Balance sheet data for U.K. banks are obtained from the S&P Global Market Intelligence data base. Specifically, we obtain, at the quarterly frequency, dealers' leverage ratios, Tier 1 capital ratios, and liquidity coverage ratios. The leverage ratio is defined as Tier 1 capital over the total leverage exposure measure, the Tier 1 capital ratio as Tier 1 capital over total risk-weighted assets and the liquidity coverage ratio as total high-quality liquid assets over total net cash outflows expected over a 30-day period of stress. The first two ratios measure the banks' resilience to negative shocks to the value of their assets. The liquidity coverage ratio measures banks' ability to withstand deposit and other short-term funding outflows in times of stress.

Table 6 reports descriptive statistics for these regulatory ratios. The average leverage ratio equals around 5 percent, exceeding the minimum of 3 percent by a comfortable margin. The Tier 1 capital ratio is on average 15.8 percent (compared to a minimum requirement of 6 percent) and the average liquidity coverage ratio in our sample is 135 percent (compared to a minimum requirement of 100 percent).

4 A structural model for the Bank of England's gilt QE auctions

Unlike many previous papers analyzing QE auctions, our data are unique because it includes not only to the winning bids but also to the ones that were not accepted. This means that our data allow us to see the complete bid curves, essentially demand curves for cash in exchange for gilts, albeit strategically modified due to the auction process. The key advantage is that only when all bids are observed can we hope to infer bidders' beliefs about the competition they face from other participants. This is because the shapes of the submitted bid curves will reflect the beliefs about the distribution of the residual supplies of cash they might face. The key observation is that by selling a given security in the QE auction rather than in the secondary market, a dealer can transact potentially a very large quantity without an immediate impact on the market price of that security. We now discuss the formal setup of the model that allows us to infer the marginal willingness-to-sell a given gilt from the observed offer yields.

4.1 Theoretical setup

The model we use is standard in the literature on Treasury bill auctions (Hortaçsu and McAdams (2010) or Kastl (2011)) while at the same time respecting institutional details about the BoE's gilt QE auctions. Most importantly, our model assumes that the auction follows a discriminatory pricing rule and bids have to be submitted as a collection of price-quantity pairs, defining the demand curve for central bank reserves as a step-function (Kastl (2011)). Also, we allow for different securities to be sold to the auctioneer during auctions, a common practice in QE reverse auctions.

Since the BoE's QE auctions follow a discriminatory pricing rule, bidders trade off their (marginal) surplus against the probability of winning. However, the QE auctions are rather non-standard. Different securities can be sold to the auctioneer. Let p_j^t denote the price of gilt j at time t. In order to translate this environment into a more familiar framework, such as the one governing sales of treasury bills for example, we need to make the offers of different securities comparable. We achieve this goal by imposing the following assumption:

Assumption 1. $\mathbb{E}_{P_j^{t=2:45}}\left[P_j^{t=2:45}|I_{b_{t^*}}\right] = p_j^{t=2:45}\ \forall j, b_{t^*}$,

where $P_j^{t=2:45}$ denotes the random market price of security j as will prevail at 2:45 p.m., $I_{b_{t^*}}$ denotes the information set at time t^* when bid b was submitted and $p_j^{t=2:45}$ denotes the actual observed realization. This assumption essentially says that bidders are endowed with correct expectations of the 2:45 p.m. price at the time when they place their bids. In other words, the only relevant margin along which they decide on their bid is the spread over that correctly anticipated price. This assumption is supported by observations on how bidders behave during the auction: most bidders submit or modify their bids in the final minutes and seconds of an auction in order to minimize interest rate risk. Hence our assumption that they can correctly forecast the market price over a very short period of time, appears as not too strong for most bidders. If there were unobserved heterogeneity related to the "quality" of the securities (for example, if the default probability were to differ across securities due to different issuers), our approach would need to be modified to take that into account. Since the securities share the same issuer, we do not believe that unobserved heterogeneity is material in our environment and instead we opt for modeling the dealers as making their bids correctly anticipating the 2:45 p.m. spread each bid ultimately translates to when the winning bids are determined by the BoE (Section 2.2).

Normalizing the submitted bids by the ex post observed price allows us to homogenize all offers and express them as one curve. Since offers are expressed in yield spreads over the 2:45 p.m. yield, it might be easier to view the auction as one in which bidders bid for a share of the offered cash amount—that is, submit their bids as if they were demand curves that are non-increasing in the yield (or to be precise, yield spread over the prevailing 2:45 p.m. yield). This is essentially a standard model of Treasury bill auctions. In what follows we thus adopt the usual terminology of bidders submitting demands that specify a share of the unit good at a given yield.

In what follows, bidders are indexed by $i \in \{1, ..., N\}$. To respect the institutional details, we further assume that the bids have to be submitted as a collection of price-quantity pairs $\{q_{ik}, b_{ik}\}_{j=1}^{K_i}$, which define a step-function demand curve, where K_i is the number of steps bidder i uses. Bidders' willingness-to-pay—that is, the maximal yield at which they are willing to "buy" q units of offered central bank reserves, is given by a function $v(q, S_i)$, where S_i is a possibly multidimensional privately observed signal (corresponding for example to the opportunity cost of using the security as collateral) distributed according to a CDF $F_i(S)$. Bidders' total value for quantity q given signal S_i is denoted by $V(q, S_i) = \int_0^q v(q, S_i)$. To facilitate estimation, following Kastl (2012), we make the following assumption on the valuations and on information structure:

Assumption 2. *(a) The marginal value for central bank reserves $v(q, S_i)$ is non-negative, bounded and strictly increasing in each component of S_i $\forall q$, and non-increasing and continuous in q $\forall S_i$.*

(b) The private signals are independently and identically distributed: $F(S_1, ..., S_N) = \prod_{i=1}^{N} F_i(S) = F(S)^N$.

(c) Dealers are risk neutral.

This assumption imposes ex ante symmetry and, more importantly, that values are "private" as the marginal value for central bank reserves are independent of private signals of rival bidders. Since the QE operations are auctions where dealers essentially swap securities that would need to be traded on the secondary market with some illiquidity discount for immediate liquidity, most dealers' bidding behavior will be driven by dealer-specific opportunity costs and immediate liquidity needs, thus justifying the private value assumption. While some common value component due to the potential differential information about the resale value of the illiquid securities might still be present, we believe one can regard it as of second order. The main reason being that the secondary market still exists, and hence any arbitrage opportunity can be taken advantage of there. Once we accept that any trading based on resale-value-relevant information takes place immediately, at any given point the uncertainty about the resale value is symmetric, and hence this information structure fits into the private value paradigm. Assumption 2 further imposes independence and identical distribution of signals across bidders, which substantially simplifies estimation. The final part of Assumption 2, risk neutrality, implies that dealers are indifferent between a fair bet on trading at two different prices at 2:45 p.m. versus trading with certainty at their expectation. This assumption is made for convenience; risk aversion could be brought into the model, but it would require some further data variation to identify the risk aversion parameters. [12]Furthermore, the assumption of risk-neutrality is supported by discussions with BoE staff running the auctions. We note that under risk aversion, our estimates of rents would be an upper bound: bidders that are risk averse, would prefer to eliminate the uncertainty arising due to the auction process and thus would bid more aggressively in a discriminatory auction, much like in a standard first price sealed bid auction.

Under these assumptions the expected utility of a bidder of a particular type s_i who submits a curve $\{q_{ik}, b_{ik}\}_{k=1}^{K_i}$ in a discriminatory auction can be written as follows:

$$\begin{aligned}\mathbb{E}_{S_{-i}}U(s_i) \quad = \quad & \sum_{k=1}^{K_i}\left[\Pr\left(b_{ik} > P^c > b_{ik+1}|s_i\right)V\left(q_{ik}, s_i\right) - \Pr\left(b_{ik} > P^c|s_i\right)b_{ik}\left(q_{ik} - q_{ik-1}\right)\right] \\ & + \sum_{k=1}^{K_i}\Pr\left(b_{ik} = P^c|s_i\right)\mathbb{E}_{S_{-i}|s_i}\left[V\left(Q_i^c, s_i\right) - b_{ik}\left(Q_i^c - q_{ik-1}\right)|b_{ik} = P^c\right] \end{aligned} \qquad (1)$$

[12]Häfner (forthcoming) describes how a share auction with risk averse bidders could be estimated.

where we let $q_{i0} = b_{iK_i+1} = 0$. P^c is the (random) market clearing yield spread and Q_i^c is the (random) quantity share allocated to i. Both random variables are functions of the vector of private signals of all market participants as they are impacted through the equilibrium strategies. A *Bayesian Nash Equilibrium* in this market consists of a profile of strategies, one for each dealer, that maps each dealer's private signal S_i into a set of admissible offer curves and maximizes equation (1) for (almost) every realization of the signal.

Under the assumption of rational expectations and optimal bidding behavior, both of which are standard in the empirical auction literature, we can use the distribution of the submitted bid curves to estimate bidders' beliefs about their rivals' play (see, for example, Guerre et al. (2000) or Hortaçsu and McAdams (2010)) and then find the value that rationalizes the observed bid. Let the offer curve (or bid) by dealer i in this auction be described by a vector $\{(b_k, q_k)\}_{k=1}^{K_i}$ satisfying $b_k < b'_k \; \forall k' > k$—that is, by a step function with K_i steps. If each bidder maximizes (expected) profits, Kastl (2012) shows that the optimal bid curve in a discriminatory auction with bidding constrained to the choice of a step function will satisfy:

$$\underbrace{v\left(q_k, s_i\right)}_{\text{Willingness-to-sell}} = \underbrace{b_k}_{\text{Offer spread}} + \underbrace{\frac{\Pr\left(b_{k+1} \geq P^c | s_i\right)}{\Pr\left(b_k > P^c > b_{k+1} | s_i\right)}\left(b_k - b_{k+1}\right)}_{\text{Rent accruing to dealers from participating in the auctions}} \tag{2}$$

where P^c is the market clearing yield spread. P^c is a random variable from the perspective of each bidder, s_i is private information of bidder i, q_k is the quantity of central bank reserves demanded in the auction at k^{th} step of the bid curve and b_k is the yield-spread at which q_k is demanded. This equation, therefore, reveals that the uncertainty about rivals' play and hence about the market clearing yield spread introduces a wedge between dealers' bids and their willingness-to-accept for a particular security (which could be determined by the opportunity cost of keeping it or selling it in the secondary market). In particular, a bidder with the marginal willingness-to-sell for a particular gilt, v, will optimally offer this gilt at a price $b > v$ and the difference, or rent, will be a function of the uncertainty about the market clearing price.[13] Notice that selling a larger quantity will result in a (weakly) lower market

[13]No auction protocol could eliminate these rents fully due to private information dealers have.

clearing price - hence there might be price impact even when selling in the QE auctions. The extent of this price impact depends on the bids submitted by rival dealers. Equation (2) hence implicitly defines a non-increasing bid curve (or demand curve) of a bidder with type s_i. In absence of uncertainty about P^c, the dealer would demand as much central bank reserves as to equate her marginal value and the clearing yield spread (whenever an interior solution exists). Note that the beliefs about the distribution of the market clearing yield spread, which enter in equation (2), are potentially specific to each dealer as the distribution of the market clearing yield spread may be determined by this dealer's bid. The variation in shapes of the submitted bids (for example, their locations and slopes) both within and across dealers and auctions and also across gilts within an auction allows us to identify this uncertainty about the market clearing yield under the assumption of optimal bidding.

4.2 Structural estimation

By inspecting equation (2), it can be seen that in order to recover the marginal values that would rationalize a given observed bid, we need to estimate the distribution of the market clearing yield spread. Given Assumption 2—that is, that each dealer draws independently a signal S_i from an identical distribution $F(s)$—one can estimate this distribution by following a resampling technique proposed in Hortaçsu and McAdams (2010). It closely resembles the bootstrap approximation of a population distribution as it involves drawing with replacement $N-1$ bids from the sample of observed bids. After subtracting these bids from the pre-announced "supply" (here this is simply the amount to be purchased in the auction), each such draw results in one possible realization of the residual supply (how much of central bank reserves is left at a given yield spread after satisfying all other bidders). Intersecting these residual supplies with each bidder's bid curve, one can obtain an estimate of the whole distribution of the market clearing yield spread for each bidder. This distribution can be plugged into equation (2) in order to recover the private information rents and ultimately the marginal value rationalizing each individual bid. To aggregate rents and marginal values from the bid-level to the dealer-level, we compute averages weighted by the offer amount.

To sum up, the structural estimation allows us to decompose the observed bids into dealers' willingness-to-sell and the usual private information rents. The following Section provides some insights on rents, while Section 6 analyses the willingness-to-sell.

5 The Bank of England's QE auctions as a backstop for secondary market liquidity

In the context of gilt QE auctions, private information rents measure the gains from trade accruing to dealers from participating in the auctions as opposed to liquidating gilts in the secondary market, potentially causing prices to change. This is because a dealer's willingness-to-sell in an auction can be viewed as her expectation of the price she would get if the trade were to take place in the secondary market instead.

Therefore, these rents can also be interpreted as liquidity benefits: by participating in the BOE's QE auctions, successful dealers exchange gilts that can be illiquid in the secondary market during times of market dysfunction against liquid central bank reserves. Hence, these rents can be informative about how effective gilt QE auctions have been as a backstop for secondary market liquidity.

On average, liquidity benefits are 3.1bps, suggesting that dealers would expect to face a significant price impact if they needed to raise liquidity using their gilt holdings on the secondary market.[14] The bootstrap standard error is about 0.08bps suggesting that the estimate is statistically significant at all conventional levels. The tiny standard error is driven likely by the estimate being the average across all auctions - and thus the sampling error washes out. To the extent that the goal of the central bank is to provide liquidity to dealers in a non-targeted way, no mechanism would be able to fully eliminate these liquidity benefits because of the usual private information rents.[15]

Liquidity benefits are higher for longer-dated gilts. In particular, they range from around

[14]Our estimate of rents in QE auctions is in line with previous estimates obtained for primary markets, or even below that. In primary auctions, these rents are reflecting opportunity costs of using the funds elsewhere. For example, Hortaçsu et al. (2018) report that for Treasury bill auctions, this number ranges from a fraction of a basis point for most liquid securities, over 0.7bps for a 52 weeks to 13.07bps for a 5 year bond and 22.2bps for a 10 year bond. Rents or liquidity benefits in Canada or the Czech Republic have been estimated at around 5-8bps (Kastl (2012)). However, some of these securities have rather different characteristics compared with gilts.

[15]Dealers have private information on how liquidity constrained they might be, how diversified they are and how much price impact they would need to cope with if they were to adjust their positions to get liquidity, and also on the likelihood of that liquidity-constrained state arising.

2.5bps in the short maturity bucket to around 3.5bps in the long bucket (Panel (a) of Figure 6). Compared with shorter-dated gilts, longer-dated gilts trade with a larger price impact in the secondary market, explaining why the willingness-to-sell and hence the liquidity benefit associated with them is larger.

Liquidity benefits are largest during times of market dysfunction. They are with 4bps largest during QE1 taking place in the immediate aftermath of the Global Financial Crisis and declined to around 2.5bps during subsequent waves of QE when market functioning had normalized (Panel (b) of Figure 6). This pattern is consistent with previous work suggesting that QE is particularly effective when introduced in dysfunctional markets (Vissing-Jorgensen (2020), Busetto et al. (2022), Bernanke (2020), Hauser (2022)). Via the so-called liquidity channel, central bank asset purchases can improve market liquidity in times of turmoil. This state-contingency can arise because in impaired markets, liquidity premiums are larger and more sensitive to policy intervention.

Hence, by providing liquidity to dealers in an anonymous and price-insensitive way, QE auctions reduce dealers' need for distressed selling to meet their demand for liquidity (Vlieghe (2020), Duffie (2023)). [16] For example, the targeted and temporary QE purchases carried out by the BoE in September 2022 backstopped liquidity in the gilt market and arrested fire sale dynamics. Such "fire sales" can, in the worst case, lead to severe market dysfunction, tighten financial conditions, amplify the weakening in the economic outlook and impair the monetary transmission mechanism.

Finally, we relate the estimated liquidity benefits or expected rents to our measure of interest rate risk and a broad range of variables characterizing dealers' bidding behavior:

$$\text{Liquidity benefit}_{a,b,d} = \alpha_a + \mu_b, +\delta_d + \beta' Z_{a,b,d} + \delta' X_{a,b} + \epsilon_{a,b,d} \tag{3}$$

where $Z_{a,b,d}$ is a vector of variables of interest that measure interest rate risk and bidding behavior, including the maximal offer amount, number of bids by gilt and the dispersion of winning bids. $X_{a,b}$ is a vector of gilt-specific controls including the free float, duration, and

[16] As put by Bernanke (2020), "A possible interpretation is that the initial [2008-2009] rounds of QE were particularly effective because they were introduced, and provided critical liquidity, in a period of exceptional dysfunction in financial markets."

the pre-auction yield change from the end of the previous day to the end of the auction. Finally, $\alpha_a, \mu_b, \delta_d$ are auction, gilt, and dealer fixed effects, respectively.

Columns (2) and (4) in Table 7 report the results. The amount of interest rate risk traded ahead of the auction does not affect liquidity benefits. Regarding variables characterizing bidding behavior, we find the higher the maximum offer amount, the lower the liquidity benefits, indicating that dealers are willing to forego some liquidity benefits to be able to sell large offers to the BoE that are costly to sell in the secondary market. The number of bids per dealer is also negatively associated with the expected rents. Finally, the more dealers compete to purchase a specific gilt, the lower the liquidity benefits.

6 Bidding behavior, interest rate risk and regulatory constraints

Section 4 described how to invert the observed bids into the actual marginal willingness-to-sell. In this section, we present some descriptive evidence about the willingness-to-sell and uncover its determinants.

To begin with, Figure 4 depicts how the marginal willingness-to-sell a given security varies across maturity sectors and QE phases. Since we normalized the bids for each security by the respective 2:45 p.m. secondary market yield, the reported values should be viewed as spreads. Positive values essentially correspond to a dealer willing to sell the security at a price that is lower than the secondary market price (or, equivalently, willingness to accept a higher yield than the secondary market yield). It follows immediately from equation (2) that bidders will not truthfully reveal their willingness-to-sell, however, due to pay-your-bid pricing. Panel (a) of Figure 4 shows that in particular for long-dated yields, dealers are willing to transact at yields that are up to 0.9bps above the 2:45 p.m. market yields.

Panel (b) of Figure 4 then shows that during QE4 dealers would require a premium relative to the secondary market prices to sell the security in the auction. This may suggest that by then they were confident that if they were unsuccessful in selling the gilts in the auction with the required premium, they could easily obtain liquidity in exchange for those securities in the secondary markets. In contrast, during all other QE phases they would be willing to transact at yields that are above the 2:45 p.m. market yields. The highest willingness-to-sell was observed during QE1 when it reached 1.4bps. QE1 took place during the height of the global financial crisis when secondary market liquidity was poor and dealers relied on the BoE to liquidate their gilt holdings.

6.1 Determinants of bidding behavior

Motivated by theory and previous empirical research, we begin by discussing various sources that might impact the way the dealers bid and then present a simple empirical model that is aimed to shed light on the bidding behavior of dealers in QE auctions.

Interest rate risk Standard market microstructure theory predicts, and empirical evidence confirms, that dealers actively manage interest rate risk, and that the amount of risk faced by dealers mean-reverts. This can be achieved by adjusting prices to incentivize risk-reducing order flow from market participants (Ho and Stoll (1981), Hendershott and Menkveld (2014)), hedging with derivative instruments (Naik and Yadav (2003)), or offloading positions anonymously in the interdealer market (Reiss and Werner (1998)). The introduction of quantitative easing offered dealers yet another attractive option to manage their interest rate risk, as the arrival of a large, predictable, and price-insensitive buyer (central bank) significantly improved their prospects of reducing unwanted (or strategically accumulated) inventory should they wish to do so. The BoE publishes a list with eligible gilts one week ahead of its auctions, thereby facilitating inventory management.

As explained in section 3.2, we approximate the amount of interest rate risk bought and sold by multiplying notional traded volumes over 2.5 days preceding each auction with the duration (DV01) of the gilt.[17] [18]

[17]In comparison, An and Zhaogang (2022) documents that for the Fed‘s MBS purchases, dealers' inventory buildup occurs over around 60 days. Each month, the Fed is publishing a schedule of its MBS purchases for the following month so dealers knew at most one month in advance that a particular MBS would be eligible, motivating their rather long window choice. In comparison, the BoE is announcing eligible gilts one week in advance. To also differentiate between unwinding inventory that has not been sold in the past auction and building up inventory ahead of the next auction, we use a window of 2.5 days.

[18]This measure should be considered as a proxy for interest rate risk as it does not take into account derivative positions or positions in other fixed income assets.

Regulatory incentives In addition, we asses if dealers' bidding behavior relates to balance sheet constraints stemming from the post-crisis regulatory reforms. While these reforms are widely believed to have strengthened the resilience of individual financial institutions and the financial system as a whole, they have also significantly affected dealers' business models and their ability and willingness to provide intermediation services (Duffie (2018), Adrian et al. (2017)), which in turn has implications for the implementation and effectiveness of monetary policy (Duffie and Krishnamurthy (2016)). A key element of the new Basel III regulatory framework was the introduction of the leverage ratio with the aim to prevent excessive build-up of leverage while avoiding the pitfalls associated with risk-based capital requirements.[19] The leverage ratio is defined as Tier 1 capital over the total leverage exposure measure, where the definition of total exposures differs across jurisdictions. In contrast to most other countries, in the U.K., central bank reserves are exempted from total exposures since August 2016. As a result, dealers can improve their leverage ratio by swapping gilts for central bank reserves via QE auctions. In contrast to the leverage ratio, dealers cannot directly improve the liquidity coverage ratio (LCR) and risk-based capital ratios by trading gilts for central bank reserves.

6.2 Econometric model

To investigate the role played by these different determinants in shaping dealers' bidding behavior, we estimate the following panel data regression:

$$Y_{a,b,d,m} = \alpha_a + \mu_m + \delta_d + \beta' Z_{a,b,d,m} + \gamma' X_{a,b,m} + \epsilon_{a,b,d,m} \tag{4}$$

where the dependent variable Y is any of the willingness-to-sell, the offered amount, or offer yield for auction a, dealer d, and gilt b in maturity bucket m; Z is a vector of variables of interest that measure the amount of interest rate risk bought and sold ahead of the auctions as well as regulatory constraints; and X is a vector of gilt-specific control variables including the free float, duration, and the pre-auction yield change from the end of the previous day

[19] Kotidis and van Horen (2018) provide a detailed overview of the design and implementation of the leverage ratio.

to the end of the auction.[20] Finally, $\alpha_a, \mu_m, \delta_d$ are auction, maturity bucket and dealer fixed effects, respectively.

6.3 Estimation results

Table 8 reports how interest rate risk accumulated prior to the auctions and the regulatory constraints affect dealers' offering behavior. Specifically, we consider three different measures of offering behavior; willingness-to-sell, offer amount and offer yield.[21] Recall that offer yields differ from the willingness-to-sell due to the liquidity benefit (equation (2)). Our baseline measure of interest rate risk is the change in the notional amount bought or sold during the 2.5 days prior to the auction multiplied by DV01 (Section 3.2). Regressions using this measure of interest rate risk are reported in columns (1)-(3) of Table 8. For comparison, columns (4)-(6) report regressions where we measure interest rate risk by the notional amount bought and sold without any duration adjustment.[22] To assess the role played by the regulatory environment in shaping bidding behavior, we focus on the leverage ratio, while controlling for the liquidity coverage ratio and the Tier 1 capital ratio. Hence, the sample is restricted to the period after the exemption of central bank reserves from the calculation of the leverage ratio was announced, that is after August 2016. As explained in Section 3.1, the data used throughout our empirical analysis is purged of offers placed on behalf of clients as they are placed with different strategical considerations compared to offers from dealers' own accounts.[23]

Our first empirical result is that dealers actively use QE auctions as an exit strategy for unwanted or strategically accumulated gilt positions. In particular, dealers who sold interest rate risk in the secondary market ahead of the auctions are less willing to participate in QE auctions. Quantitatively, the response of the willingness-to-sell to the average amount

[20] Table 6 provides descriptive statistics for the regression variables not introduced thus far.

[21] The offer amount is set to zero if a gilt was eligible but no offer was submitted. In contrast, the offer yield and willingness-to-sell are set to "missing" in these instances, which explains the different number of observations used for different dependent variables. Re-estimating the regressions for the offer amount and setting all zeros to "missing" does not affect the results reported below.

[22] Because the correlation between the volume and interest rate risk variables is around 85 percent, we do not include both measures in the same regression.

[23] When including client bids, some coefficients are less precisely estimated (table 9 in the Online Appendix).

of interest rate risk sold is 0.38 bps, comparable in size to the bid-ask spread of 0.5 bps observed in the gilt market (Belsham et al. (2017)). In addition, dealers that successfully bought gilts in the secondary market ahead of the auction offered larger amounts of gilts in the forthcoming auction. For the average amount bought ahead of the auction, the amount offered into the forthcoming auction increases by £3.5 million. By comparison, the average trade size in the gilt market is £50 million.[24]

Our second empirical result is that dealers use QE auctions to improve their leverage ratio. In particular, dealers with a lower leverage ratio have a higher willingness-to-sell. The size of this effect is economically meaningful: if the leverage ratio falls by 1 percentage point, the willingness-to-sell increases by 2.5 bps or about 5 times the average bid-ask spread in the gilt market. Although dealers forgo a higher return when exchanging gilts for reserves, this seems a price worth paying to improve their regulatory compliance. Dealers with less regulatory space also offer larger quantities for sale in the auctions. If the leverage ratio declines by 1 percentage point, dealers offer an additional £10 million into the auction, or about 1/5 of the average trade size in the gilt market. The LCR and the Tier 1 capital ratio does not affect bidding behavior in the auctions. The coefficient on the Tier 1 capital ratio is insignificant and the coefficient on the liquidity coverage ratio is statistically significant but economically negligible.

We also investigate if the effect of the leverage ratio differs at quarter ends, when dealers report their balance sheet data to the regulator and hence may have stronger incentives to improve their leverage ratios ("window dressing"). We find no evidence that this is the case in our sample period (Table 11 in the Online Appendix).

Compared to the willingness-to-sell, the effects of interest rate risk and the leverage ratio on the offer yield are insignificant. Hence, liquidity benefits exhibits time variation that can significantly alter the empirical results.

Regarding the additional control variables, we find that dealers are less willing to sell gilts to the BOE when observing their price to fall ahead of the auction, while the other control variables are not statistically significant.

[24]We also find a positive relationship between the interest rate risk bought and the number of bids placed in the subsequent auction, suggesting that dealers acquiring more interest risk place both more and larger offers.

6.4 Robustness

One concern with these results is that different gilt securities are likely to be substitutes to some degree. So a dealer's bidding strategy for a specific gilt could also be driven by interest rate risk held for a broader set of gilts with a similar residual maturity. To assess if that is the case, Table 9 also controls for interest rate risk bought and sold of gilts within 2.5 years of residual maturity, respectively. Controlling for interest rate of substitutes leaves the coefficient estimates on interest rate risk and on the leverage ratio almost unchanged in magnitude and statistical significance. One exception is the effect of interest rate risk bought on the willingness-to-sell that is statistically significant in this specification.[25]

In addition, the effects of interest rate risk and regulatory constraints on bidding behavior can vary across maturity buckets and time. Table 8 reports our estimates separately for the short, medium, and long maturity auctions (Tables 1-3 in the Online Appendix). For the amount of interest rate risk sold or bought, the largest effect is observed in the short maturity bucket. For short-dated gilts, the effect of the amount of interest rate risk sold on the willingness to sell increases to -0.81bps, while the effect of the amount of interest rate risk bought on the offer amount increases to £20mn. By comparison, the results for the medium and long maturity sector are closer to those for the full sample reported above. Regarding the leverage ratio, the largest impact is observed in the long-maturity bucket where the willingness-to-sell increases by 4.5bps.

When assessing variation in our results over time, we only focus on the relationship between interest rate risk and bidding behavior, excluding the regulatory ratios. This is because our baseline Table 8 only uses data from QE4 due to the change in the leverage ratio regulation at that time. To start with, Table 10 reports the results for interest risk bought and sold using the full sample period. In the full sample, the effect of interest rate risk on offering behavior is qualitatively similar to the results reported above. To uncover potential time variation in this effect, Tables 4-7 in the Online Appendix estimate the effect of interest rate risk bought and sold on bidding behavior by QE phase. While the effect of interest rate risk on the amount offered is broadly stable over time, the effect on the

[25] Results are also robust to using a broader definition of substitutes spanning +/- 5 years of residual maturity (Table 8 in the Online Appendix).

willingness-to-sell varies, with the the largest effects being observed during QE4.

Finally, our results are robust to using the net amount of interest rate risk bought as the main explanatory variable instead of including the amounts bought and sold separately (Table 10 in the online Appendix).

7 The cost of the Bank of England's gilt QE purchases

So far, our analysis has relied on our unique data comprising both accepted and rejected offers that has enabled us to recover dealers' private willingness-to-sell and liquidity benefits from the observed offer yields. In contrast, previous work on QE auctions has primarily used data on accepted bids only. For comparison, this section hence reports a measure of the cost of the auctions following the approach in Breedon (2018). Specifically, we compute the cost of running the auctions incurred by the BoE as the volume-weighted difference between the yield accepted by the BoE and the prevailing secondary market yield at the auction close (WAAY spread). Hence, negative values of our cost measure indicate a loss for the BoE.[26]

On average, the cost of running the auctions is -0.38 bps, implying that dealers sold the securities in the auctions at prices that are slightly higher than those prevailing on the secondary market. The cost of QE is largest for gilts in the medium and long buckets (Panel (a) of Figure 5). A potential explanation for this observed pattern is interest rate risk: toward the end of each auction, there is a short period of time between the close of the auction (after which dealers cannot modify their bids) and the announcement of the results. During that period, dealers are exposed to market risk, which is higher for long gilts, because of their longer duration. To compensate for this risk, dealers may want to submit lower yield offers for longer-dated gilts to begin with. Panel (a) of Figure 5 also indicates that dealers are making losses when selling short-duration gilts to the BoE. One possible explanation for this observation is that dealers are paying up for immediacy. Alternatively, they may also be willing to pay for turnover as only dealers with a high turnover are allowed to participate in the DMO's syndications that are attractive for dealers to obtain gilts. Panel (b) of Figure

[26]Strictly speaking, these costs should not be interpreted as pure dealer profits because they also include the cost of allocating staff and technology to participate in the auctions.

5 reports how the cost of QE spread varied across time. QE1 recorded the highest cost incurred by the BoE (-0.7bps), while that cost was essentially zero during QE3.

Overall, the cost of QE for the BoE is very small, in particular when put in perspective with the ultimate benefits of the policy. There are numerous studies documenting that the BoE's asset purchases were successful in stimulating spending and inflation to meet the BoE's inflation target of 2 percent over the medium term (Joyce et al. (2011), Busetto et al. (2022)), suggesting that the benefits of QE outweigh its cost. By participating in the auctions and by trading in the secondary market, dealers are actively facilitating the transmission of QE to the real economy, perhaps justifying a small profit.

Our estimates of the cost of QE are smaller compared with previous research. For example, measuring the cost of QE during QE1 and QE2 by comparing average accepted yields to gilt yields at the end of auction day, Breedon (2018) concludes that these programs have been expensive. Indeed, his estimates of the cost of QE1 and QE2 are almost double ours, which can be explained by the fact that Breedon (2018) uses end of day yields as a point of comparison, while we compare average accepted yields to yields prevailing in the secondary market at auction close. So the relatively large cost figures in Breedon (2018) are likely to be partially driven by news arriving after the auction close and that are unrelated to the auctions themselves.

Finally, we assess if interest rate risk and bidding behavior are related to the cost of QE. To do this, we estimate a version of (3) where the dependent variable is replaced the WAAY spread. Columns (1) and (3) in Table 7 report the estimation results. We do not find a significant effect of interest rate risk bought and sold on the WAAY spread. This implies that participating dealers may not be able to systematically increase their profits by strategically trading in the secondary market ahead of the auctions, suggesting that the BoE's QE auctions are well designed and carefully implemented. Regarding independent variables characterising bidding behavior, we find that dealers offering a larger maximum amount also offer a higher yield relative to the market yield prevailing at auction close, reducing the cost of QE. Given the auction allocation protocol used by the BoE, submitting an offer at a lower price relative to the market increases the chance of having the offer accepted. This may be a less costly way for dealers to offload large positions given the price impact associated with such large trades in the secondary market. In addition, the cover ratio and the number of bids per dealer are also negatively related to the WAAY spread. Finally, the cost of QE is positively related to duration, suggesting that gilts carrying higher interest rate risk are more costly to acquire for the BoE, consistent the descriptive statistics in Figure 5.

8 Conclusions

In this paper, we study the bidding behavior during four rounds of QE auctions implemented by the BoE between 2009 and 2017. Using a novel data set containing both accepted and rejected offers together with an equilibrium model of bidding behavior, we estimate dealers' willingness-to-sell gilts to the BoE and the rents accruing to them.

Since a dealer's willingness-to-sell in an auction can be viewed as her expectation of the price she would get if the trade were to take place in the secondary market, rents can also be viewed as liquidity benefits that the dealers accrue from participating in the auction as compared to liquidating assets in the secondary market. We document that liquidity benefits of the BoE's gilt purchases have been largest during QE1 taking place in the immediate aftermath of the global financial crisis when financial markets were dysfunctional. By providing ample liquidity in an anonymous and price-insensitive way, the BoE's QE purchases have prevented dealers from facing binding liquidity constraints that could have resulted in distressed selling and market turmoil. For policy makers, this implies that central bank facilities designed to backstop liquidity in dysfunctional market segments are most effective when implemented in a timely fashion.

In addition, we document that the amount of interest rate risk accumulated ahead of the auction and regulatory constraints play an important role in determining bidding behavior in the BoE's QE auctions. Hence, central banks should assess how regulations affecting dealers' balance sheet capacity interact with their operational framework when designing QE operations.

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Table 1: Residual maturity buckets in U.K. QE reverse auctions.

Regime	Maturity bucket	Min. maturity	Max. maturity	Start date	End date
1	M	5	10	5-Mar-2009	5-Aug-2009
1	L	10	25	5-Mar-2009	5-Aug-2009
2	S	3	10	6-Aug-2009	8-Feb-2012
2	M	10	25	6-Aug-2009	8-Feb-2012
2	L	25		6-Aug-2009	8-Feb-2012
3	S	3	7	9-Feb-2012	25-Mar-2015
3	M	7	15	9-Feb-2012	25-Mar-2015
3	L	15		9-Feb-2012	

Table 2: QE phases in the U.K..

Phase	Start date	End date
QE1	March 5, 2009	October 5, 2011
QE2	October 6, 2011	July 4, 2012
QE3	July 5, 2012	March 10, 2013
Reinvestment	March 11, 2013	August 3, 2016
QE4	August 4, 2016	March 3, 2017

Table 3: U.K. primary dealers between March 2009 and March 2017. Source: U.K. Debt Management Office (U.K. Debt Management Office (2020)).

U.K. primary dealers
Banco Santander SA, London Branch
Barclays Bank Plc
BNP Paribas (London Branch)
Citigroup Global Markets Limited
Credit Suisse
Deutsche Bank AG (London Branch)
Goldman Sachs International Bank
HSBC Bank Plc
Jefferies International Limited
J.P. Morgan Securities Plc
Lloyds Bank Corporate Markets Plc
Merrill Lynch International
Morgan Stanley & Co. International Plc
Nomura International Plc
Royal Bank of Canada Europe Limited
Royal Bank of Scotland Plc
Scotiabank Europe Plc
Societe Generale (London Branch)
State Street Bank Europe
Toronto-Dominion Bank (London Branch)
UBS Limited
Winterflood Securities Limited

Table 4: Descriptive statistics for the U.K. QE reverse auctions.

		QE phase					
	bucket	All	QE1	QE2	QE3	R	QE4
# auctions	All	352	92	78	50	51	81
	S	103	17	26	16	17	27
	M	125	38	26	17	17	27
	L	124	37	26	17	17	27
# gilts per auction	All	8.38	7.01	9.10	8.78	9.31	8.42
	S	8.43	8.94	9.65	7.25	8.35	7.67
	M	5.75	6.13	6.73	6.00	6.18	3.85
	L	11.00	7.03	10.92	13.00	13.41	13.74
# dealers per auction	All	15.7	14	17.6	16.2	16.6	14.9
	S	15.5	13.3	17.5	15.8	16.6	14.3
	M	15.5	14	17.6	15.7	16.1	15
	L	16	14.2	17.8	17.2	17.1	15.3
Offered per auction (GBP mn)	All	2389	3323	2582.3	1680	2084.8	1771.0
	S	2444.1	3281.6	3139.3	1611.4	2346.7	1802.0
	M	2587.4	3468.7	2556.3	1941.6	2187.4	2035.7
	L	2143.1	3192.4	2051.2	1483.1	1720.4	1475.4
Purchased per auction (GBP mn)	All	893.1	1288.9	1009.1	579.2	957.2	485.2
	S	773	788.5	991	583	977.3	537.2
	M	919.2	1239.6	1062	588.6	960.7	512.7
	L	966.6	1569.5	974.3	566.4	933.7	405.7

Notes: The Table reports descriptive statistics for the gilt QE auctions carried out by the BoE between 2009 and 2017 by QE phase and residual maturity bucket. QE1-QE4 denote the four different QE phases and R denotes reinvestments (Table 2). S, M, L stand for the short, medium and long maturity sector, respectively (Table 1).

Table 5: Descriptive statistics for dealers' trading activity in the secondary market.

	Allocated	Offered	Eligible	Ineligible
Volume bought (GBP million)	90.57	92.44	43	42.99
Volume sold (GBP million)	81.42	85.64	42.77	43.73
Interest rate risk bought (GBP million)	1180.49	1160.98	555.88	475.81
Interest rate risk sold (GBP million)	1056.26	1075.41	550	481.49

Notes: The table reports averages for both interest rate risk and traded volumes accumulated by dealer and gilt during the 2.5 days preceding each auction. The sample period is from 2011 to 2017.

Table 6: Descriptive statistics for regulatory ratios, gilt characteristics and further auction variables.

Statistic	Mean	Median	Min	Max	St. Dev.
Gilt characteristics					
Free float (GPB mn)	20,771.38	20,872.00	2,249.00	36,025.00	7,753.21
Duration (GBP per bps change in yield)	10.38	7.04	0.003	62.23	10.41
Pre-auction yield change (bps)	−1.18	−1.00	−25.10	15.90	3.99
Additional U.K. QE reverse auction variables					
Max. offer amount (GPB mn)	28.87	25	1	100	25.01
No. bids per dealer	2.13	2.00	1.00	8.86	0.98
No. bids per gilt	2.34	2.00	1.00	26.00	1.51
Dispersion of winning bids	0.06	0.03	0.00	1.30	0.09
Regulatory ratios					
Leverage ratio (percent)	5.32	5.00	3.40	7.40	1.14
Liquidity cov. ratio (percent)	134.91	127.00	112.00	204.75	22.91
Tier one capital ratio (percent)	15.80	15.58	12.10	20.04	2.41

Notes: Data on gilt characteristics are from the U.K. Debt Management Office, the BoE and Bloomberg. Regulatory returns are from S&P Global Market Intelligence and are available at quarterly frequency. The sample period is from 2009 to 2017.

Table 7: Liquidity benefits, the cost of U.K. QE reverse auction, bidding behavior and secondary market trading.

	WAAY spread	Rent	WAAY spread	Rent
Interest rate risk bought (GPB bn)	−0.01	0.02		
	(0.01)	(0.08)		
Interest rate risk sold (GPB bn)	0.001	−0.08		
	(0.01)	(0.10)		
Volume bought (GPB bn)			−0.06	−0.19
			(0.08)	(0.91)
Volume sold (GPB bn)			−0.06	−0.44
			(0.07)	(1.05)
DV01	0.01**	−0.01	0.01**	−0.01
	(0.003)	(0.02)	(0.003)	(0.02)
Free float (GPB mn)	−0.002	0.01	−0.002	0.005
	(0.002)	(0.01)	(0.002)	(0.01)
Pre-auction yield change (bps)	−0.02	−0.14*	−0.02	−0.13
	(0.01)	(0.08)	(0.01)	(0.08)
Max. offer amount (GPB mn)	0.002***	−0.01***	0.002***	−0.01***
	(0.0004)	(0.004)	(0.0004)	(0.004)
Cover ratio by bond	−0.0003*	−0.002	−0.0003	−0.002
	(0.0002)	(0.002)	(0.0002)	(0.002)
Offer amount by bond	−0.0000	−0.0003	0.0000	−0.0003
	(0.0001)	(0.0004)	(0.0001)	(0.0004)
No. bids per dealer	−0.03**	−0.39***	−0.03**	−0.40***
	(0.01)	(0.09)	(0.01)	(0.09)
No. dealers per bond	−0.02	−0.69***	−0.02	−0.72***
	(0.03)	(0.27)	(0.03)	(0.27)
Dipersion of winning bids	−0.51	1.28	−0.53*	1.14
	(0.31)	(1.10)	(0.31)	(1.09)
Maturity bucket FE	*Yes*	*Yes*	*Yes*	*Yes*
Auction FE	*Yes*	*Yes*	*Yes*	*Yes*
Dealer FE	*Yes*	*Yes*	*Yes*	*Yes*
No. auctions	81	81	81	81
Observations	5,344	5,344	5,344	5,344
Note:				*p<0.1; **p<0.05; ***p<0.01

Notes: The table reports estimation results from equation (3). Standard errors are clustered by gilt. The cost of QE is measured as the weighted average accepted yield relative to the market yield at auction close. The liquidity benefit is measured as the surplus accruing to dealers from participating in the auctions. Cost and liquidity benefit are expressed in bps. The sample period is 2011 to 2017.

Table 8: Participant's offering behavior in U.K. QE reverse auction, interest risk and regulatory constraints.

	Willingness-to-sell	Offer yield	Offer amount	Willingness-to-sell	Offer yield	Offer amount
Interest rate risk bought (GPB bn)	0.10	0.33	0.003^{**}			
	(0.10)	(0.33)	(0.001)			
Interest rate risk sold (GPB bn)	-0.35^{***}	-0.06	0.002			
	(0.09)	(0.42)	(0.001)			
Volume bought (GPB bn)				1.51	0.51	0.08^{***}
				(1.09)	(7.48)	(0.02)
Volume sold (GPB bn)				-4.84^{***}	-5.57	0.02
				(1.52)	(6.25)	(0.03)
DV01	0.04	0.43	-0.0002^{***}	0.04	0.42	-0.0001
	(0.03)	(0.39)	(0.0001)	(0.03)	(0.38)	(0.0001)
Free float (GPB bn)	-0.01	-0.17	-0.0001	-0.03	-0.10	-0.0001
	(0.03)	(0.42)	(0.0002)	(0.03)	(0.42)	(0.0002)
Pre-auction yield change (bps)	-0.51^{*}	5.44^{**}	0.003^{*}	-0.47	5.35^{**}	0.003^{*}
	(0.29)	(2.64)	(0.002)	(0.29)	(2.69)	(0.001)
Leverage ratio (percent)	-2.45^{**}	0.24	-0.01^{*}	-2.54^{***}	0.59	-0.01^{*}
	(0.99)	(3.09)	(0.005)	(0.97)	(3.14)	(0.005)
Liquidity cov. ratio (percent)	-0.03	0.07	-0.0002^{*}	-0.03	0.07	-0.0002^{**}
	(0.02)	(0.11)	(0.0001)	(0.02)	(0.11)	(0.0001)
Tier one capital ratio (percent)	-0.10	0.50	-0.001	-0.03	0.49	-0.002
	(0.61)	(1.15)	(0.003)	(0.60)	(1.24)	(0.003)
Maturity bucket FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Auction FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Dealer FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
No. auctions	81	81	81	81	81	81
Observations	1,080	1,080	4,818	1,080	1,080	4,818

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Notes: The table reports estimation results from equation (4). Standard errors are clustered by gilt. Willingness-to-sell and offer yield are in bps, and offer amount is in £billion. The sample is restricted to the period after the exemption of central bank reserves from the calculation of the leverage ratio was announced, that is after August 2016 (coinciding with QE4).

Table 9: Participant's offering behavior in UK QE reverse auction, interest rate risk and regulatory constraints: including trading in gilt substitutes (+/- 2.5 yrs of residual maturity)

	Willingness-to-sell	Offer yield	Offer amount	Willingness-to-sell	Offer yield	Offer amount
Interest rate risk bought (GPB bn)	0.14*	0.45	0.003**			
	(0.08)	(0.28)	(0.002)			
Interest rate risk sold (GPB bn)	−0.33***	0.04	0.002			
	(0.10)	(0.38)	(0.001)			
Interest rate risk of substitues bought (GPB bn)	0.003	0.05*	−0.0000			
	(0.005)	(0.03)	(0.0000)			
Interest rate risk of substitutes sold (GPB bn)	−0.004	−0.05	0.0000			
	(0.005)	(0.03)	(0.0000)			
Volume bought (GPB bn)				1.63	4.29	0.08***
				(1.04)	(4.85)	(0.02)
Volume sold (GPB bn)				−4.74***	−3.17	0.02
				(1.45)	(5.53)	(0.03)
Volume of substitutes bought (GPB bn)				0.05	0.47*	0.0001
				(0.04)	(0.27)	(0.0003)
Volume of substitutes sold (GPB bn)				−0.06	−0.52**	−0.0001
				(0.04)	(0.26)	(0.0004)
DV01	0.03	0.41	−0.0002	0.03	0.28	−0.0001
	(0.04)	(0.34)	(0.0001)	(0.04)	(0.32)	(0.0001)
Free float (GPB bn)	−0.02	−0.18	−0.0001	−0.03	−0.16	−0.0001
	(0.03)	(0.39)	(0.0002)	(0.03)	(0.34)	(0.0002)
Pre-auction yield change (bps)	−0.49*	5.39**	0.003	−0.48	5.53**	0.003
	(0.29)	(2.54)	(0.002)	(0.29)	(2.43)	(0.002)
Leverage ratio (percent)	−2.44**	0.17	−0.01*	−2.50***	1.16	−0.01*
	(0.99)	(2.99)	(0.005)	(0.97)	(3.08)	(0.005)
Liquidity cov. ratio (percent)	−0.03	0.05	−0.0002*	−0.03	0.10	−0.0002**
	(0.02)	(0.10)	(0.0001)	(0.02)	(0.09)	(0.0001)
Tier one capital ratio (percent)	−0.09	0.44	−0.001	−0.05	0.26	−0.002
	(0.61)	(1.24)	(0.003)	(0.60)	(1.22)	(0.003)
Maturity bucket FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Auction FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Dealer FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
No. auctions	260	260	260	260	260	260
Observations	1,080	1,080	4,818	1,080	1,080	4,818

Note: *p<0.1; **p<0.05; ***p<0.01

Notes: The table reports estimation results from equation (4). Standard errors are clustered by gilt. Willingness-to-sell and offer yield are in bps, and offer amount is in £billion. The sample is restricted to the period after the exemption of central bank

Table 10: Participant's offering behavior in U.K. QE reverse auction and interest rate risk: full sample period.

	Willingness-to-sell	Offer yield	Offer amount	Willingness-to-sell	Offer yield	Offer amount
Interest rate risk bought (GPB bn)	0.04	0.92***	0.004***			
	(0.05)	(0.35)	(0.001)			
Interest rate risk sold (GPB bn)	−0.14***	0.59**	−0.0003			
	(0.04)	(0.27)	(0.001)			
Volume bought (GPB bn)				−0.12	7.91	0.07***
				(0.56)	(4.84)	(0.01)
Volume sold (GPB bn)				−1.39***	8.19	−0.01
				(0.52)	(5.01)	(0.01)
DV01	−0.05	1.96**	−0.0001	−0.05*	1.99**	−0.0001
	(0.03)	(0.76)	(0.0001)	(0.03)	(0.77)	(0.0001)
Free float (GPB bn)	−0.01	−0.62*	0.0002	−0.01	−0.58	0.0002
	(0.02)	(0.36)	(0.0001)	(0.02)	(0.36)	(0.0001)
Pre-auction yield change (bps)	−0.05	1.02	0.002***	−0.04	1.00	0.002***
	(0.13)	(2.55)	(0.001)	(0.13)	(2.55)	(0.0005)
Maturity bucket FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Auction FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Dealer FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
No. auctions	260	260	260	260	260	260
Observations	10,312	10,312	47,863	10,312	10,312	47,863

Note: *p<0.1; **p<0.05; ***p<0.01

Notes: The table reports estimation results from equation (4), excluding regulatory ratios. Standard errors are clustered by gilt. Willingness-to-sell and offer yield are in bps, and offer amount is in £billion. The sample period is 2011 to 2017.

Figure 1: Time line of a typical QE auction at the BoE.

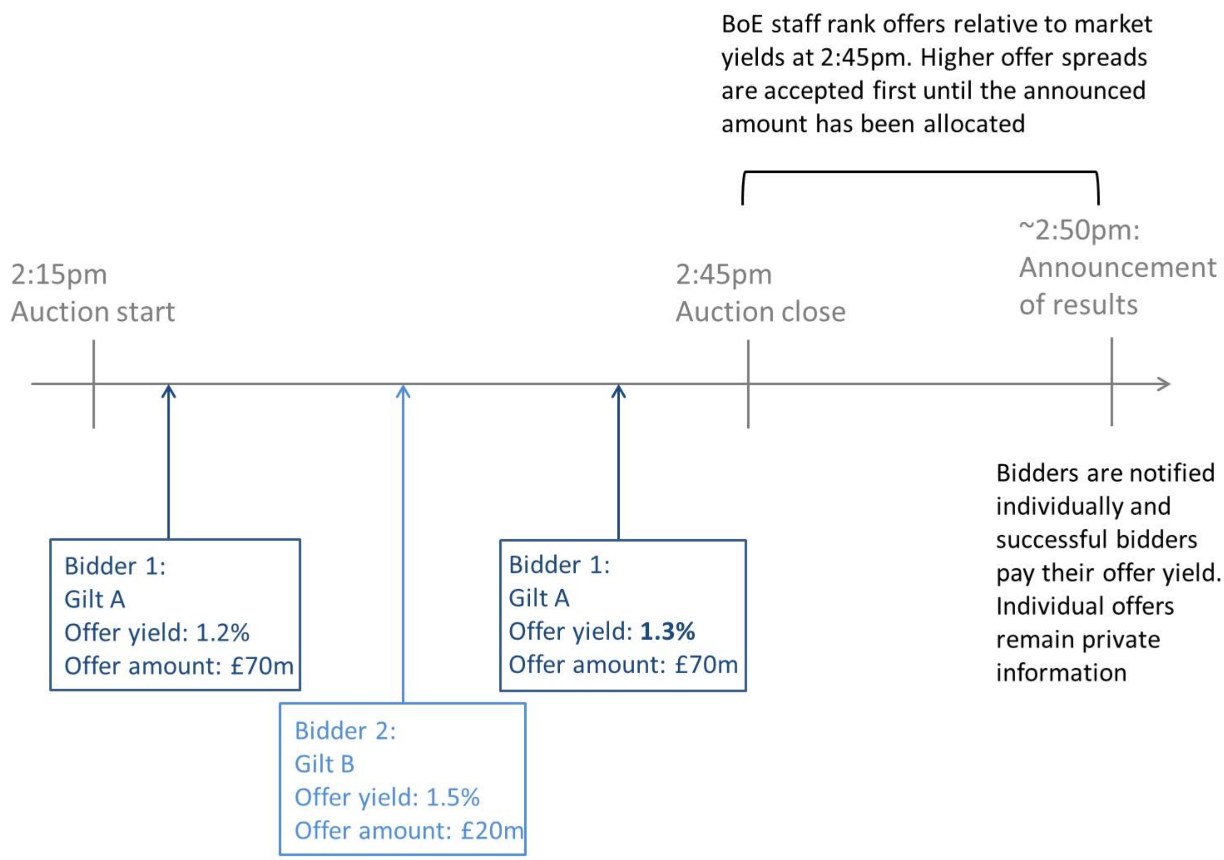
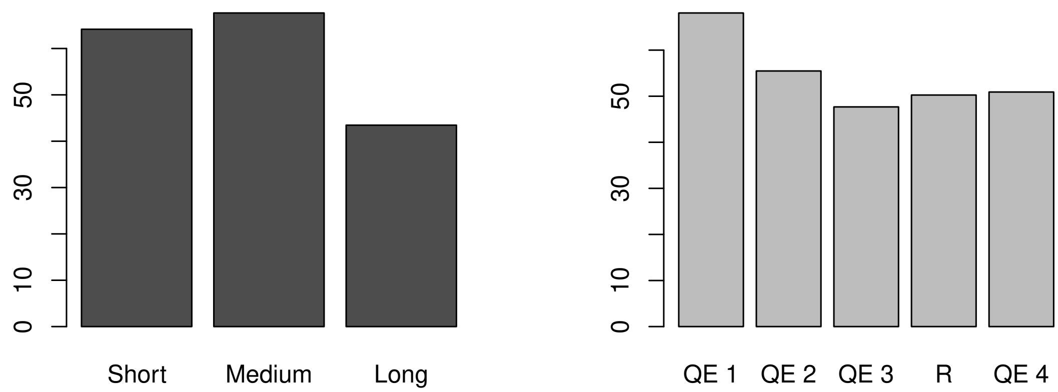


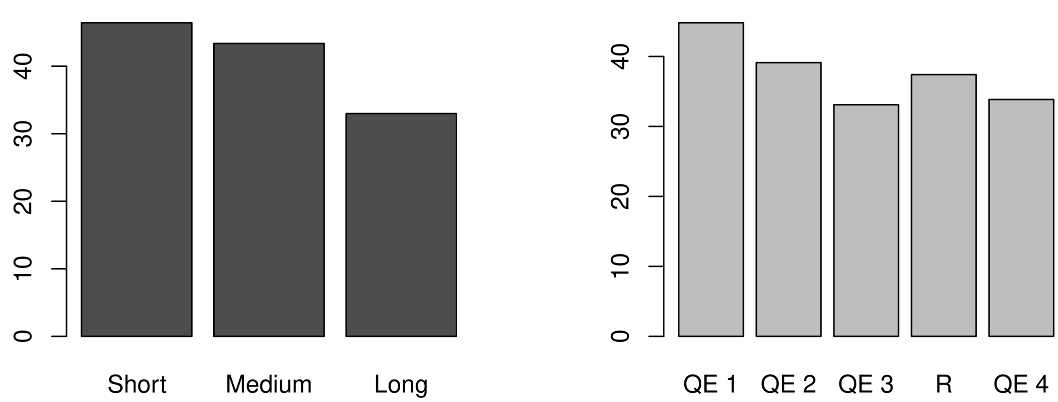
Figure 2: Average offer amount by gilt and dealer by maturity bucket and QE phase.



(a) by maturity bucket (b) by QE phase

Notes: The average offer amount is in £million. The sample period is 2009 to 2017.

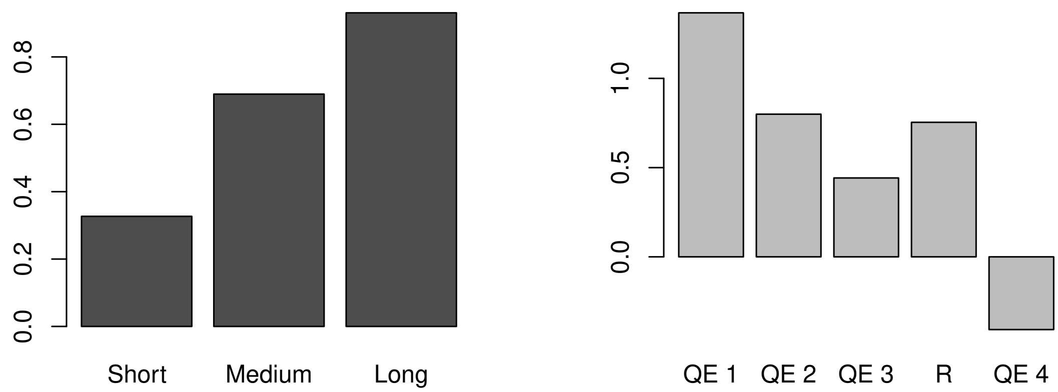
Figure 3: Average accepted amount by gilt and dealer by maturity bucket and QE phase.



(a) by maturity bucket (b) by QE phase

Notes: The average accepted amount is in £million. The sample period is 2009 to 2017.

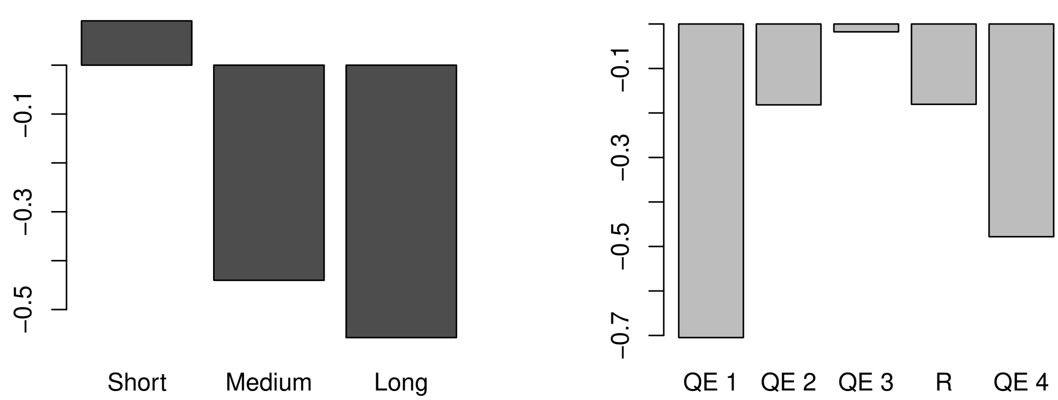
Figure 4: Willingness-to-sell by maturity bucket and QE phase.



(a) by maturity bucket (b) by QE phase

Notes: The willingness-to-sell is in bps. A positive willingness-to-sell correspond to a dealer willing to sell the security at a price that is lower than the secondary market price. The sample period is 2009 to 2017.

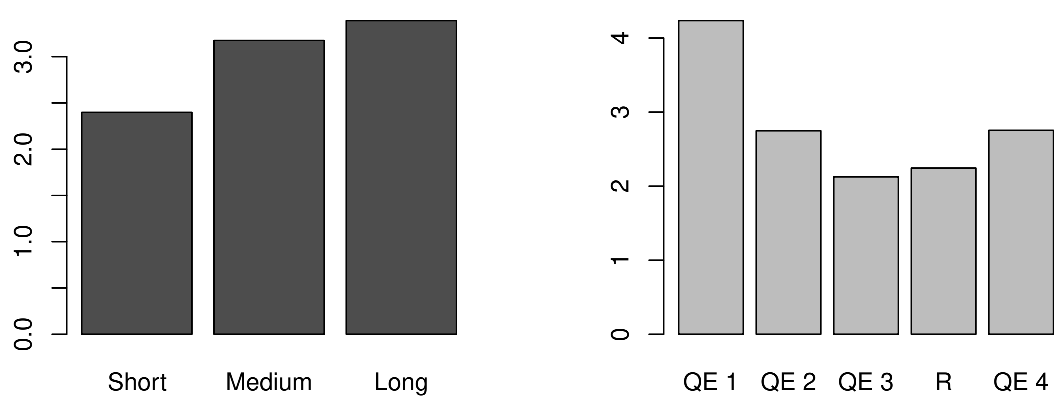
Figure 5: Cost of QE by maturity bucket and QE phase.



(a) by maturity bucket (b) by QE phase

Notes: The cost of QE is in bps. The cost of QE is measured as the weighted average accepted yield relative to the market yield at auction close and negative values indicate that the BoE was purchasing gilts at prices that are above those prevailing in the secondary market. The sample period is 2009 to 2017.

Figure 6: Liquidity benefits by maturity bucket and QE phase.



(a) by maturity bucket (b) by QE phase

Notes: Liquidity benefits are in bps. The liquidity benefit is the surplus accruing to dealers from participating in the auctions. The sample period is 2009 to 2017.