Dealer balance sheets and bidding behavior in the UK QE reverse auctions*

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Abstract

What is driving dealers' bidding behavior in the Bank of England's QE reverse auctions? To tackle this question, we estimate dealers' valuations of securities offered to the Bank of England using a novel dataset on both accepted and rejected offers together with an equilibrium model of bidding behavior. Dealers' valuations and the amount offered vary significantly with the amount of interest rate risk acquired in the secondary gilt market prior to the auction and with dealers' regulatory capital. Our estimates of valuations can be viewed as dealers' expectations of secondary market prices if they transacted same volumes there and caused prices to change. The QE auctions thus may act as a mechanism that lowers price volatility in the gilt market.

Keywords: quantitative easing, reverse auctions, dealer balance sheets, structural estimation.
JEL codes: E52, D44, C57.

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1 Introduction

In response to the 2008 financial crisis, many central banks lowered their policy rates to near zero and engaged in unconventional monetary policy operations such as outright asset purchases, commonly known as Quantitative Easing (QE). In the United Kingdom (UK), the Bank of England (BoE) purchased £435 billion worth of UK government bonds (the so-called gilts) in four rounds of QE between 2009 and 2017 and became the single largest investor in the gilt market, currently holding almost 30% of the outstanding stock of UK government debt. More recently, QE has seen a revival in policy packages implemented following the sharp deterioration in the economic outlook after the Covid-19 outbreak. For example, in March 2020, the BoE announced it will purchase an additional £200 billion of government bonds and sterling non-financial investment-grade corporate bonds.

The BoE implements asset purchases via weekly reverse auctions, where primary dealers competed to sell eligible assets to the BoE. Given the key role played by primary dealers in these sizable operations, it is important to understand the factors that drive their bidding strategies and how their bidding behavior affects auction outcomes. This has implications for the cost of implementing quantitative easing and for the implementation of monetary policy more broadly.

In this paper, we address these questions using a novel proprietary dataset that contains offers submitted by 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 all offers submitted to each auction, including those that were ultimately rejected by the BoE. This allows us to trace out dealers' offer curves and perform a structural estimation to recover dealers' marginal valuations for each offered security. We combine these data with audit-trail transaction-level data for individual gilts in the secondary market, enabling us to link dealers' bidding behavior with their trading activity in the secondary market ahead of each auction. Additionally, since many of the primary dealers participating in the UK reverse auctions also act as primary dealers in the United States (US), we complement the UK data with the publicly available data on Permanent Open Market Operations (POMO) conducted by the Federal Reserve during our sample period. To the extent that global dealer banks manage their liquid asset positions and risks globally, their bidding behavior in the UK may be affected by the outcomes of recent reverse auctions in the US and we look for such a link. Finally, the overhaul of the regulatory landscape in the aftermath of the financial crisis affects banks' demand for safe assets and thus their willingness-to-sell these assets to central banks. To study the impact of these regulations on bidding behavior, we make use of regulatory filings that are available for most banks in our sample.

Armed with this novel granular data, we first structurally estimate dealers' marginal values using the method developed in Hortaçsu and McAdams (2010), Kastl (2011) and Hortaçsu and Kastl (2012). The basic idea is to use the variation in bids (particularly, the levels and slopes of the bid curves) to estimate 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 hence submitting bids that maximize their expected profits, one can then recover for any observed bid the corresponding marginal valuation or, as is the case in QE auctions, 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 is to the best of our knowledge the first structural analysis of QE reverse auctions.

Having obtained the estimates of dealers' willingness-to-sell, we then turn to the main objective of the paper and study the determinants of dealers' bidding behavior in the BoE's QE reverse auctions. Our main point of departure is the fact that holding interest rate risk on their balance sheet is costly and hence dealers actively manage their interest rate exposures. The desire to contain these exposures stems from dealers' attitudes towards risk (Ho and Stoll (1981)), internal risk-management constraints (Amihud and Mendelson (1980), Adrian and Shin (2010)), financing constraints (Brunnermeier and Pedersen (2008), He and Krishnamurthy (2013)) or regulatory constraints, such as capital and liquidity requirements (Adrian et al. (2017)) and restrictions on proprietary trading (Iercosan et al. (2019)). As we discuss in more detail below, these balance sheet constraints imply that dealers set targets for their inventory risk and so we expect that the amount of risk they hold on their balance sheet going into an auction will affect their offers placed during QE auctions.

To shed light on this question, we use our transaction records from the secondary gilt market to calculate the amount of gilts dealers bought and sold in a two-and-a-half day period ahead of each auction and the interest rate risk associated with it.

We then use our measure of interest rate risk to predict dealers' willingness-to-sell a specific gilt and the amount offered. Consistent with implications from finance theory, our results suggest that dealers' willingness-to-sell and the amount offered increase in the interest rate risk bought and/or decrease in the interest rate risk sold in the secondary market pre-auction. For the average amount of interest rate risk sold (£1.1 bn), the willingness-to-sell falls by around 0.2bps. This effect is largest during the fourth wave of QE where the willingness-to-sell declined by about 0.44bps for the average amount of interest rate risk sold, and increased by about 0.42bps for the average amount of interest rate risk bought. These estimates are comparable to the average bid-offer spread in the gilts market of around 0.5bps (Belsham et al. (2017)). The effect of interest rate risk on the amount offered can be sizable, too. For the average amount of interest rate risk bought (£1.2bn), the amount offered into the forthcoming auction increases by £12mn. That effect is largest for short-dated gilts where the offer amount increases by £22mn, or almost 1/2 of the average offer size.

In addition to domestic interest rate risk, we also consider interest rate risk that dealers sell or buy by participating in concurrent US QE auctions. Primary dealers participating in the UK and US QE auctions largely overlap suggesting that dealers' bidding behavior in a UK auction may be affected by their purchases and sales of US Treasury securities in previous US QE auctions. Specifically, an alternative way to managing sterling interest rate risk for a globally operating market maker is to trade in non-sterling interest rate instruments that closely co-move with sterling ones, such as the US Treasury securities. Through these proxy hedges, purchases of UK gilts may be offset by sales of Treasuries, and vice versa, potentially generating spillovers between the US and UK QE operations. In addition, motivated by the evidence that large banks manage their liquidity globally (Cetorelli and Goldberg (2012a), Cetorelli and Goldberg (2012b)), we expect that primary dealers common to both US and UK QE auctions – which are all large global dealer banks – manage their interest rate risk and liquid asset positions globally and treat the sovereign debt of countries with similar credit quality as substitutes. However, we do not detect much evidence that dealers coordinate their participation in QE programs across borders. Instead of through the Fed, these trades may take place in the secondary market for US Treasuries.

Finally, we consider how the regulatory landscape affects dealers' bidding behavior. Following the financial crisis of 2008, a significant effort has been put into strengthening the resilience of the financial system. Regulatory capital requirements for banks were overhauled, new liquidity requirements introduced, and restrictions on proprietary trading by deposit-taking institutions imposed (e.g. Duffie (forthcoming), Tarullo (2019)). Some of these new regulations affect banks' demand for safe assets and thus their willingness-to-sell these assets in QE auctions. Specifically, following an exemption rule implemented in 2916, UK banks can improve their leverage ratios by exchanging gilts for central bank reserves. Consistent with these regulatory incentives, we find that a one percentage point fall in the leverage ratio increases the amount offered by around £20mn. This increase is economically significant given that the average offer size is around £65mn.

Having documented how balance sheet and regulatory constraints affect dealers' bidding behavior in the reverse QE auctions, the final part of the paper asks how these constraints affect auction outcomes, with a particular focus on the cost of QE. Similar to Song and Zhu (2018), we measure this cost by the volume-weighted difference between the yield the BoE pays for a gilt acquired in the reverse auction and the secondary market yield prevailing at the time the auction closes (WAAY spread). On average, the WAAY spread is negative but relatively small with just -0.3bps, suggesting that dealers are making a small profit by participating in the auctions. But that profit is small compared to the ultimate benefits of the policy, that is, achieving the BoE's inflation target.[1] The WAAY spread ranges between 0.1bps for short gilts and -0.5bps for long gilts, indicating that realized profits accruing to participating dealers are concentrated on the long part of the yield curve.

Because by a standard no-arbitrage argument a dealer's willingness-to-sell in an auction can be viewed as her expectation of price she would get if the trade were to take place in the secondary market, our structural estimation allows us to estimate implied rents that the dealers accrue from participating in the auction. These rents can be viewed as costs of reducing volatility in the gilt market and preventing dealers from facing liquidity constraints and thus endangering financial markets. Auctions allow the Bank of England to provide liquidity to dealers in an anonymous way by

[1]There are numerous studies documenting that the BoE's QE policy was successful in promoting growth and achieving the inflation target (Joyce et al. (2011)), suggesting that the benefits of QE outweigh its cost. By participating in the auctions and by trading in the secondary markets, dealers are facilitating the transmission of QE to the economy, perhaps justifying some profits.

leveraging competition between them. To the extent that the goal of the mechanism is to provide liquidity to dealers in a non-targeted way, no mechanism would be able to eliminate these rents fully due to the usual private information rents. Dealers' rents cannot be interpreted directly as the cost of QE.[2] The average expected rent accruing to dealers is equal to 2.6bps, suggesting that they would face a sizeable price impact if they had to trade in the secondary market and prices might thus become quite volatile. Rents vary across maturities too, with 2bps for short-dated gilts and 3bps for long-dated ones.

Finally, we estimate the effects of bidding behavior and trading activity in the secondar market on our measure of expected rents and on the cost of QE. There is no evidence of strategic trading in the secondary market ahead of the auctions that would increase the rents accruing to dealers or cost of QE to the Bank, suggesting that the auctions are well designed and carefully implemented.

There is a mature literature on the effect of QE on asset prices and the macroeconomy (D'Amico and King (2013), Joyce and Tong (2012),D'Amico and Kaminska (2019), Vissing-Jorgensen and Krishnamurthy (2013), Hamilton and Wu (2011), Del Negro et al. (2017), Christensen and Rudebusch (2012), D'Amico et al. (2012), Krishnamurthy et al. (2018), Raskin et al. (2011)). For example, D'Amico and King (2013) study stock and flow effects of QE on Treasury yields using a range of methodologies including instrumental variable estimation. Using an event study analysis, Joyce and Tong (2012) estimate the announcement effect of QE auctions on yields during the first round of QE in the UK. D'Amico and Kaminska (2019) document significant spill-overs from the UK's gilt QE purchases on corporate bond spreads. While these papers assess the impact of asset purchases on range of asset prices, our paper zooms in on the QE auctions themselves.

Our paper is more 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 QE auctions of Treasury bonds in the US between November 2010 and September 2011. In a related paper, Bonaldi et al. (2015) assess dealer

[2] For example, in absence of QE auctions, dealers facing liquidity shocks might face substantial price impact when trading and ultimately might be in need of direct intervention, which could cost the tax payers substantially more. The cost of QE would need to be evaluated relative to the costs of maintaining functioning financial markets in the absence of these auctions. This calculation would thus involve probabilities of various states of the world where the financial system might need help and its cost.

profits and efficiency in the Federal Reserve Board's treasury QE auctions and MBS auctions. Finally, Breedon (2018) computes the "round-trip" costs of issuing gilts in the primary market and purchasing them via QE reverse auctions. These papers use publicly available auction outcomes and market prices. Compared to these papers, we make several novel contributions to the literature on QE reverse auctions. To start with, we utilize a novel dataset recording both accepted and rejected offers, allowing us to perform a structural estimation of a model of equilibrium bidding. This approach allows us to estimate dealers' private willingness-to-sell that rationalizes the observed offer prices and quantities taking into account the uncertainty faced by the participants and to study the determinants of bidding behavior in QE auctions. It also allows us to compare the observed cost as measured by the WAAY spread with the rents accruing to the dealers from participating in the auctions, which has not been done before in the context of QE reverse auctions.

Finally, this paper is related to the literature studying the cost and efficiency of primary auctions of government securities (Hortaçsu et al. (2018), Hortaçsu and Kastl (2012), Kastl (2011), Han et al. (2007), Hortaçsu and McAdams (2010),Hortaçsu and Sareen (2006)). [should we elaborate?]

The remainder of this paper is organized as follows. Section 2 explains the design of QE auctions in the UK and the structure of the UK government bond market. Section 3 describes the three data sets employed in the paper and Section 4 discusses the structural estimation methodology for extracting dealers' willingness-to-sell. Section 5 reports our empirical results and Section 6 analyses the costs of QE. Finally, Section 7 concludes.

2 Institutional background

2.1 Quantitative easing in the UK

After the policy rate in the UK was lowered to 0.5% in early 2009 to achieve the inflation target over the medium term, the Monetary Policy Committee (MPC) of the BoE announced on March 5, 2009 that it would undertake outright purchases of UK government bonds (gilts). The initial stock of purchases amounted to £75bn but increased to £200bn in the period until February 2010. In 2011 and 2012, the purchases were further extended to £300 and £375 billion, respectively. Following the UK's European Union membership referendum in July 2016, the MPC announced a further round of QE purchases worth £60bn.[3] Finally, in response to the deteriorating economic outlook after the Covid-19 outbreak, the BoE's MPC announced to purchase an additional £200 billion of government bonds and sterling non-financial investment-grade corporate bonds on March 19, 2020. Between different rounds of QE, the stock of QE purchases was maintained by reinvesting the principle amount of maturing gilts. Figure 1 shows the evolution of the BOE's gilt holdings by the BoE and Table 1 reports the exact sub-sample periods corresponding to the various phases of QE in the UK for the period from 2009 to 2017.

The asset purchases were financed by creation of central bank reserves and formally carried out by the Bank of England Asset Purchase Facility Fund Limited (APF) which is a subsidiary of the BoE. The APF is indemnified by Her Majesty's Treasury against losses associated with its QE operations and any profits from the APF portfolio are returned to the Treasury.

2.2 The design of reverse QE auctions in the UK

To implement QE, the BoE uses a multi-object, multi-unit, discriminatory price reverse auction format.[4] Eligible participants include the participants in the BoE's gilt-purchase Open Market Operations (OMOs) and the Gilt-Edged Market Makers (primary dealers) as listed on the website of the UK's Debt Management Office (DMO). Each participant is allowed to submit an unlimited number of offers containing price, quantity, and the bond identifier. Information about the offers is private.

The auctions are conducted on a weekly basis and are scheduled from 2:15 to 2:45pm.[5] 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

[3] In addition to conventional gilts, the Bank of England also bought private sector assets such as corporate bonds. While some corporate bond purchases took place at the start of the QE programme, the majority of these purchases took place in 2016/2017 after the announcement of the Corporate Bond Purchase Scheme in August 2016.

[4] 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`

[5] In addition to the competitive auctions, some participants are eligible to sell bonds in a non-competitive auction at the average accepted price determined in the competitive auction. Only 1% of the purchases are non-competitive (Joyce and Tong (2012)).

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 2).

In the week ahead of each auction, the BoE publishes a list of eligible bonds. In general, the purchases conducted by the APF exclude gilts with residual maturity less than 3 years, gilts of which the BoE already holds more than 70% of free float, index-linked gilts, and gilts with an issue size of £4 billion or less. Gilts that are newly issued by the DMO in the week preceding the auction or those that will be re-opened by the DMO either one week before or after the auction are also excluded. The BoE's transparency about what is and is not eligible in its gilt QE auctions enables primary dealers to know well in advance which gilt can be offered into which auction and manage their inventories accordingly.

Figure 2 uses an example to graphically illustrates how the auctions are run in practice. Dealers submit their offers to sell eligible gilts to the BoE between 2:15 to 2:45pm on auction days. 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 receive their offer price, meaning that all purchases are undertaken on a discriminatory price basis. Ahead of 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.[6]

After the close of each auction, the BoE publishes aggregate auction results including quantities offered and allocated. Individual offers remain private to bidders and the BoE.

2.3 UK secondary gilt market

The UK primary dealers (GEMMs) play a vital role in the secondary gilt market. They are required to provide liquidity to market participants by quoting bid and ask

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

prices on a continuous basis in all market conditions. In return, they are eligible to participate in the UK Debt Management Office's (DMO) primary auctions and related operations. The vast majority of trading in the secondary gilt market is carried out over-the-counter (OTC) and a small amount occurs on the London Stock Exchange.[7]

There were 61 different conventional gilts traded at some point in time during our sample period, including both gilts issued prior to the beginning of the sample period as well as gilts issued during the sample period. The number of primary dealers varies during our sample period, as some firms resigned their GEMM status, while new firms acquire it. In total, there were 22 different GEMMs during the sample period and Table 3 lists these firms.

2.4 Quantitative easing in the US

Similar to the UK, QE in the US proceeded in multiple stages. The first round, which primarily involved purchases of mortgage backed securities (MBS) was initiated in November 2008 and concluded in March 2010. In August 2010, the Federal Open Market Committee (FOMC) started a second round of asset purchases, acquiring a total of $778bn worth of Treasury bonds through September 2011. Furthermore, in September 2011, the FOMC announced the so-called Maturity Extension Program (MEP) aimed at flattening the yield curve. This program involved buying long-term Treasury bonds and selling Treasury bills. Finally, in September 2012, the FOMC announced a third round of QE, purchasing mortgage backed securities and $40bn worth of Treasury bonds per month until the spring of 2013, when the FOMC decided it would gradually reduce the asset purchases as the US economy continued to improve. The QE program officially ended in October 2014, and the Fed started to unwind its balance sheet in October 2017. However, following the outbreak of Covid-19, the FOMC announced on March 15, 2020 that it will increase its holdings of Treasury and MBS by $500 and $200bn, respectively, to promote smooth functioning of these markets. On March 23, 2020, the FOMC included agency commercial MBS in its MBS purchases, and stated that it will continue purchases of Treasury and MBS securities in the amounts necessary to achieve its objectives.

[7]Benos and Zikes (2018) and Bicu et al. (2017) provide a detailed description and analysis of the UK gilt market structure.

3 Data

3.1 UK QE auction data

Our auction data set covers 352 QE auctions that took place between March 2009 and March 2017. As illustrated in Figure 1, the majority of these purchases are concentrated in four distinct phases, known as QE1-QE4. 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 provides detailed information at the offer level. This includes the identity of the dealer, the gilt to be sold to the BoE, the offer price and quantity, and the allocated amount (which can be zero). In contrast to the US data used by Song and Zhu (2018), 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 prices that prevailed in the secondary market at the close of the auction (2:45pm).

Table 4 reports some summary statistics for the auction data, broken down by QE phase and residual maturity. With the exception of QE1, where purchases concentrated in medium-term and long-term bonds, the number of auctions was similar across the three residual maturity buckets. The average number of eligible bonds per auction was fairly constant over time and ranged from 5.75 for medium-maturity gilts to 11 for long-maturity gilts. The average amount offered per bond stood at £481.5 million. The median sector received with £700.7 million on average the highest offered amount per bond. The BoE purchased £214.5 million per bond on average, or around 45% of the average offered amount, and £48.3 million on average per winning offer. Almost all auctions were well covered, in particular auctions for bonds within the short maturity bucket and during QE4.[8]

3.2 Transaction records from the UK secondary gilt market

Our secondary market transaction data is obtained from the ZEN database maintained by the UK Financial Conduct Authority (FCA). Each transaction record contains the trading account of the reporting party, transaction date and time, gilt ISIN,

[8]There was a case of an uncovered auction in August 2016 with a shortfall amounting to £52 million.

execution price, size of the transaction, buyer/seller flag, agency/principle capacity flag, reporting party name and frequently, but not always, the identity of the counterparty. Large dealer banks have typically 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 by Kondor and Pinter (2019), who develop a fixed-point algorithm and show that it successfully identifies the market-making accounts of the primary dealers in the gilt market.[9] [10]

Once we have isolated dealers' accounts related to their own trading activity, we aggregate notional volumes bough and sold across these accounts to construct measures of trading activity for each dealer and gilt. Because we aim to use secondary market activity to predict offering behavior, notional volumes bought and sold are accumulated over 2.5 days ahead of each auction.[11] In a next step, we compute a measure of interest rate risk that dealers accumulated before each auction by multiplying the volume bought or sold of each gilt in the secondary market by the gilt's DV01, which measures the change in the value of a bond with a 1 basis point change in its yield.[12]

Table 5 reports descriptive statistics for both interest rate risk and traded volumes by bond and dealer. On average, we find that the average amount of interest rate risk and notional volume bought by dealers in eligible and ineligible gilts (columns (3) and (4)) are similar to those sold. But for gilts that are offered into the subsequent auction and/or purchased, the risk and volume bought exceeds the risk and volume sold.

[9]For robustness, we also experiment by selecting, for each dealer, only those trading accounts that exhibit a large, two-way trading activity. The correlation between the traded volume computed using either method is around 95% and all regression results are robust to identifying market-making accounts using the alternative method.

[10]We are grateful to Gabor Pinter for sharing his list of market-making accounts by dealer with us.

[11]Specifically, traded volumes is accumulated on the auction day itself until the start of the auction at 2:15pm 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.

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

3.3 UK dealer balance sheet data

Balance sheet data for UK banks are obtained from S&P Global Market Intelligence. Specifically, we obtain, at the quarterly frequency, the dealers' leverage ratios, capital ratios, and liquidity coverage ratios. The leverage ratio is defined as Tier 1 capital over total leverage exposure measure; the capital ratio is defined as total equity capital (Tier 1 plus Tier 2) over total risk-weighted assets; and the liquidity coverage ratio is defined 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 some summary statistics for these regulatory ratios. The average leverage ratio equals around 5% and exhibits a considerable dispersion across banks. The Tier 1 capital ratio is well above the regulatory minimum for all banks, with an average of 15.8%. The average liquidity coverage ratio in our sample is 135%.

3.4 US QE auction data

The US QE auction data include all Permanent Open Market Operations (POMO) involving US Treasury securities executed by the Federal Reserve Bank of New York (FRBNY) on behalf of the FOMC between August 17, 2010 and October 27, 2014. Our sample period therefore covers QE2, MEP, and QE3. The data are obtained from the website of the FRBNY and identify for each winning offer the purchased or sold amount, price, bond CUSIP, and dealer identity. Information on unsuccessful bids and offers is not publicly available. During the sample period, the FRBNY conducted 710 reverse auctions, purchasing $2.4 trillion worth of Treasury bonds, and 75 auctions, selling $640 billion worth of Treasury bills. All auctions were sealed-offer, multi-unit, multi-object, and discriminatory-price auctions (Song and Zhu (2018)). As shown in Table 7, $12-13$ bonds were purchased or sold on average per auction and around 15 dealers participated in a typical auction. All auctions were well-covered, especially those where the Fed was selling Treasury bills.

As for UK QE reverse auctions, we compute the volume and interest rate risk bought and sold by US primary dealers that also participate in UK QE reverse auctions. But in contrast to the UK measures of interest rate risk that are computed for each dealer and gilt separately, those for the US are aggregated across US Treasuries bought or sold by a participating dealer in US QE auctions taking place during two days ahead of UK QE reverse auctions.

4 Estimating the marginal willingness-to-sell

Unlike previous papers analyzing QE auctions, our data is unique in that we have access not only to the winning bids, which have been made available publicly in the US (as used in Song and Zhu (2018)), 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. The key advantage is that only when the full bids are observed can we hope to infer bidders' beliefs about the competition they face. 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. We now discuss the formal setup of the model that allows us to infer marginal willingness-to-sell a given bond from the observed spread offers using methods from empirical analysis of treasury bill auctions such as in Hortaçsu and McAdams (2010) or Kastl (2011).

4.1 Theoretical setup

Since the QE auctions in the UK follow a discriminatory pricing rule, bidders trade off (marginal) surplus against the probability of winning. However, as described in the section above, the QE auctions are rather non-standard. Different securities can be sold to the auctioneer. Let p_j^t denote the price of bond 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 be shown on Reuters screen at 2:45pm, $I_{b_{t^*}}$ 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 2:45pm 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. So for most bidders, we assume that they can correctly forecast the market price over a window of a few minutes or seconds, which is not too strong. 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 a big problem in our environment and instead we opt for modeling the dealers as making their bids correctly anticipating the 2:45pm spread each bid ultimately translates to when the winning bids are determined by the auctioneer (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 2:45pm yield, it might be easier to view the auction as one in which bidders bid for a share of the offered cash amount, i.e., 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 2:45pm 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.

To respect the institutional details (Section 2.2), we assume that the bids have to be submitted as a collection of price-quantity pairs, which define a step-function demand curve. Bidders willingness-to-pay, i.e., 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 $F_i(S)$. 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* $\frac{\partial V_i(q,S_i)}{\partial q} = v\left(q, S_i\right)$ *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, private values 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 time 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 2:45pm 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 these parameters. One could substantiate risk neutrality by observing that if some dealers were risk averse, there should be demand for derivatives that would eliminate the uncertainty connected with the trading later in the day at the expected price p at a somewhat worse price, $p' < p$, i.e., that at least one risk neutral party with deep pockets would be able to offer such a derivative and make positive expected profits.

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:

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

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 of these 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 $b_k < b'_k \ \forall k' > k$, i.e., 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:

$$
\underbrace{v\left(q_k, s_i\right)}_{\text{willingness-to-sell}} = \underbrace{b_k}_{\text{offer spread}} + \underbrace{\frac{\Pr\left(b_{k+1} \geq P^c|s_i\right)}{\Pr\left(b_k > P^c > b_{k+1}|s_i\right)}\left(b_k - b_{k+1}\right)}_{\text{strategic effect}} \qquad (2)
$$

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 accept for a particular bond, v, will optimally offer this bond at a price $b > v$ and the difference, or markup, will be a function of the uncertainty about the market clearing price. 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 (e.g., their locations and slopes) both within and across dealers and auctions and also across bonds within an auction allows us to identify this uncertainty about the market clearing yield under the assumption of optimal bidding.

4.2 Structural estimation

Inspecting equation (2), it is easy to see 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, i.e., 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 preannounced "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 market clearing yield spread for each bidder. With this distribution, we can plug in to equation (2) in order to recover the marginal value rationalizing each individual bid.

4.3 Empirical results

Figure 3 and Table 4 depict how marginal valuations or, as is the case in QE auctions, the marginal willingness-to-sell a given security, vary across maturity sectors and QE phases. Since we normalized the bids for each security by the respective 2:45pm secondary market yield, the marginal values should be viewed as spreads. Positive marginal 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 3 shows that for short maturities dealers would require a slight premium relative to the secondary market prices to sell the security in the auction. However, for long maturities they would be willing to transact at yields that are up to 60bps above the 2:45pm market yields. One possibility rationalizing this pattern is that the price impact of large quantities of long term bonds transacted in the secondary market would lead to a much larger price impact than in the short maturities. Panel (b) then shows that the first three waves of the QE program in the UK were all similar in terms of dealers' willingness to transact in the QE auctions: their marginal willingness-to-sell was about 50bps above the 2:45pm market yield. Interestingly, during the fourth wave, in contrast, they demanded a substantial premium relative to the 2:45pm secondary market price to transact in the auction. This may suggest that by then they were confident that if they were unsuccessful in selling the bonds in the auction with the required premium, they could easily obtain liquidity in exchange for those securities in the secondary markets.

We now take our estimates of marginal willingness-to-sell that rationalize the observed bids and use these together with potential determinants of dealers' bidding behavior in order to better understand the bidding in QE auctions.

5 Bidding behavior, interest rate risk and regulatory constraints

In the previous Section we discussed how to invert bids into the actual marginal willingness-to-sell by estimating the strategical component that arises because dealers don't know about their rivals' play. This section aims at explaining the willingness-to-sell together with the offered amount. Motivated by theory and previous empirical research, we begin by discussing the 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 the QE auctions.

5.1 Determinants of bidding behavior

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. Thus, we expect that dealers who accumulate interest rate risk in eligible gilts ahead of QE auctions are more willing to sell their positions to the central bank and offer larger amounts in order to bring their interest rate risk closer to target.

Although we do not have direct data on interest rate risk in gilts and related instruments, our data allow us to calculate the change in these positions ahead of each auction. We use these changes to proxy for the changes in the amount of interest rate risk faced by the dealer. As explained in section 3.2, interest rate risk is computed by multiplying notional volumes bought and sold over 2.5 days preceding each auction with the DV01 of the gilt.

An alternative way to managing sterling interest rate risk for a globally operating market maker is to trade in non-sterling interest rate instruments that closely co-move with the sterling ones, such as the US Treasury securities. Through these proxy hedges, purchases of UK gilts may be offset by sales of Treasuries, and vice versa, potentially generating spillovers between the US and UK QE operations. These spillovers may also arise if dealers manage their liquid asset positions globally, treating closely co-moving sovereign bonds as substitutes for the purposes of meeting their liquidity targets. Cetorelli and Goldberg (2012a) and Cetorelli and Goldberg (2012b) present evidence that is consistent with this notion: large global banks tend to manage their liquidity globally.

To assess if interest rate risk accumulated in foreign safe assets matters for dealers' bidding behavior, we exploit the large overlap between dealers participating in UK QE auctions and those participating in the US ones. As shown in Table 3, out of the 22 primary dealers operating in the UK gilt market, 17 also serve as primary dealers in the US Treasury market. All of these "common" dealers are large international banks, so to the extent that these banks manage their liquidity globally, we expect their bidding behavior in the UK auctions to be affected by their recent activity in the US auctions.

Among the different phases of QE in the US, the programs that overlapped with the BoE's QE operations were QE2, Operation Twist (Maturity Extension Program), and QE3 that took place from 2010 to 2014. In the QE2 and QE3 programs, the Fed was only purchasing US Treasury securities, while in the MEP program, the Fed sold short-term Treasury securities (bills) and purchased long-term Treasuries (bonds) with the aim to flattening the yield curve.

To assess whether non-sterling interest rate risk matters for bidding behavior in the BoE's QE auctions, we thus restrict our sample to the duration of these three operations and to dealers participating in both US and UK operations only.

Regulatory incentives. Finally, 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 (forthcoming), 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. [13] 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 UK, central bank reserves are exempted from total exposures since August 2016. This implies that banks can improve their leverage ratio by swapping gilts for central bank reserves via QE auctions. We therefore expect that banks with lower leverage ratios would be more willing to sell their positions and offer larger amounts in these auctions than banks facing a less binding leverage constraint.

To control for the confounding effect of other regulations, we include in our empirical specification dealers' liquidity coverage ratio (LCR) and a risk-based capital ratio. Dealers cannot directly improve these regulatory ratios by trading gilts for central bank reserves.

5.2 Econometric model

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

$$Y_{a,b,d} = \alpha_a + \mu_b + \delta_d + \beta' Z_{a,b,d} + \gamma' X_{a,b} + \epsilon_{a,b,d} \quad (3)$$

where the dependent variable $Y_{a,b,d}$ is any of the offered amount, offer yield or the willingness-to-sell, $Z_{a,b,d}$ is a vector of variables of interest that measure interest rate risk and regulatory constraints and $X_{a,b}$ is a vector of bond-specific control variables including the free float, duration, and the pre-auction yield change from the end of the previous day to the end of the auction. Table 6 provides descriptive statistics for the regression variables not introduced thus far. Finally, $\alpha_a, \mu_b, \delta_d$ are auction, bond, and dealer fixed effects, respectively.

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

5.3 Empirical results

We start by investigating the effect of domestic interest rate risk accumulated prior to the auctions on dealers' offering behavior (Table 8). Specifically, we consider three different measures of offering behavior, willingness-to-sell, offer amount and offer yield. In contrast to the willingness-to-sell, offer yields are contaminated by a strategic element so we report the results for offer yields for comparison only and do not discuss them in much detail. Our baseline measure of domestic interest rate risk is the change in the notional amount bought or sold over 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.[14][15]

The regression results suggest that dealers that sold more interest risk associated with a specific gilt have a lower willingness-to-sell the gilt in question and offer a lower amount. In addition, the amount of interest rate risk bought is positively related to the amount offered in the subsequent auction.[16] Taken together, these results tend to suggest that dealers who sold their gilt inventory at favorable conditions in the secondary market ahead of the auctions do not use the BoE' auctions as an exit strategy. But dealers with unwanted or strategically accumulated interest risk in eligible gilts actively use the BoE's QE auctions to reduce these positions.

To assess if these results matter quantitatively, recall from Table 5 that the average amount of interest rate risk sold in the secondary market in the 2.5 days preceding each auction is around £1.1bn for offered gilts, translating into a decline in the willingness-to-sell by around 0.2 bps or about 1/2 of the average bid-offer spread in the gilt market (Belsham et al. (2017)). In addition, the offer amount declines by just over £1mn, which is small compared with the average offer size of about £65mn. Consistently,

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

[15]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 all full-sample regressions for the offer amount reported in this section when setting all zeros to "missing" does not affect the results reported below. Results are reported in Table 28 in the Online Appendix.

[16]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 (Table 29 in the Online Appendix).

the amount of interest rate risk bought increases the willingness-to-sell and the offer amount but is only statistically significant for the latter. For the average amount bought of around £1.2bn for offered gilts (Table 5), the amount offered into the forthcoming auction increases by £12 mn or about 1/5 of the average offer size.

Turning to the control variables, a lower free float is associated with a higher willingness-to-sell. Intuitively, the free float measures the amount outstanding that is potentially available for trading, that is, not held by the central bank or the government. So our results suggest that dealers are more willing to sell scarce gilts which are likely to be more costly to sell in the secondary market due to search frictions, for example. In addition, the BoE only purchases gilts if it does not own too much of them already, that is, if the free float is relatively large. So this result is also consistent with dealers exhibiting a higher willingness-to-sell gilts that are about to become ineligible.

In addition, we find that dealers offer a larger amount if a gilt has experienced a larger pre-auction yield change. Differently put, when observing the price of an eligible gilt to fall ahead of the auction, dealers tend to offer a larger amount. In that case, dealers perhaps expect the price to fall further and use the BoE auctions as a price-insensitive way to reduce their holdings. All results are robust to measure interest rate risk by gilt volumes bought and sold in the secondary market without duration adjustment (columns (4)-(6)).

The regression analysis so far treats all gilts offered in an auction equally. However, as is well-known, long-maturity gilts are more sensitive to interest rate changes due to their larger duration, so dealers may have a stronger incentive to offload longer-dated gilts compared with short-term gilts in an auction. To empirically assess if the relationship between interest rate risk and bidding behavior depends on the residual maturity of a bond, we estimate Table 8 separately for the short, medium, and long maturity auctions. Results are reported in Tables 1-3 in the Online Appendix. For the willingness-to-sell, the effect of interest rate risk is indeed only statistically significant for the long-maturity sector, where an average increase in interest rate risk sold (£1.1bn) decreases the willingness-to-sell by 0.24bps. For the offer amount, the reverse pattern is observed: the largest coefficient estimate is observed for short-dated gilts, where for the average amount of interest rate risk bought (£1.2bn), the offer amount increases by about £22mn. This increase is economically significant compared with the average offer amount of around £65mn.

In addition to variation across bonds, there is likely to be variation across time as our sample covers both tranquil times and times of financial market dislocations, such as e.g. after the UK's European Union membership referendum. To investigate how our estimation results vary over time, Tables 12-15 in the Online Appendix estimate the results in Table 8 by QE phase. Qualitatively, our results tend to hold over time, but quantitatively, there is significant variation. For the willingness-to-sell, the effect of interest rate risk is strongest during QE4 where the willingness-to-sell declined by 0.44 bps for the average amount of interest rate risk sold (£1.1 bn). During QE4, the amount of interest rate risk bought is also significant. For the average amount bought of around £1.2 bn, the willingness-to-sell increased by 0.42 bps. These estimates are comparable in size to the average bid-offer spread in the gilt market of 0.5bps (Belsham et al. (2017)). In contrast, interest rate risk has the largest impact on the offer amount during QE2 and the reinvestment period.

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, Tables 25 and 26 in the Online Appendix also control for interest rate risk of gilts within 2.5 or 5 years of residual maturity, respectively. Our results are robust to controlling for interest rate risk in gilt substitutes, regardless of the bucket size. For the smaller bucket size of 2.5 years, interest rate risk of substitutes bought and sold is not statistically significant. When choosing a larger bucket size of 5 years, the effect of interest rate risk of substitutes on the willingness-to-sell is statistically significant but the coefficient estimates are smaller compared to those of the interest rate risk related to the specific gilt the offer was placed for.

Another concern is that some offers are placed by dealers on behalf of their clients who may follow a different offering strategy compared to dealers' own accounts. While there is no formal way of distinguishing client offers, we control for this by assuming the largest offers are likely to be placed by hedge fund clients and Table 30 in the Online Appendix removes offers larger than £100mn. Hedge fund clients may also be more likely to submit more speculative offers at prices significantly above those prevailing at the time of the auction. As another robustness check, we therefore remove these offers from our estimation (Table 31 in the Online Appendix).[17] In both cases, removing these extreme and perhaps quite different offers does not qualitatively change our results.

In Table 9, we add our measures of US interest rate risk to investigate if the amount of interest rate risk acquired by the dealers in US QE auctions affect their bidding behavior in the subsequent UK auctions. In these regressions, we only include primary dealers that are active in both the UK and US (Table 3) and we focus on the overlapping periods between UK QE1-3 (including re-investments) and the Maturity Extension Programme in the US as well as US QE2 and QE3. We find that that most the measures of US interest rate risk are not statistically significant. An exception is the amount of interest rate risk sold to the Fed, which is positively related to the offer amount in the subsequent UK auction, indicating that dealers selling Treasuries to the Fed also try to sell gilts to the BoE. But this coefficient is only marginally statistically significant and quantitatively small, implying only an £0.4 mn increase in the offer amount in a BoE auction for a $1bn increase in their sales to the Fed. Estimating the same regression specification for different UK and US QE phases and for the different maturity buckets does not produce different results (Tables 4, 5 and 16-20 in the Online Appendix).[18]

Finally, Table 10 assesses how the regulatory landscape affects bidding behavior. To do so, we restrict our sample to the period after the exemption of central bank reserves from the calculation of the leverage ratio was announced, that is after August 2016 and to dealers where regulatory returns are available. The results are therefore driven by the last phase of quantitative easing in the UK, QE4. Because there were no permanent open market operations conducted in the US during this period, the variables related to US interest rate risk are not included in the regression. We find that while the leverage ratio has no significant effect on the willingness-to-sell, dealers with a lower leverage ratio offer larger quantities for sale in the auctions. Although banks forgo a higher return when exchanging gilts for reserves, this seems a price worth paying to improve their regulatory compliance. The effect is economically

[17] In particular, we compute the distribution of weighted offer yields relative to the market yields at auction close and remove the offers below the 1th percentile. This is done separately for the different QE phases and maturity buckets.

[18] Results for the short maturity bucket are not reported because of an insufficient number of US auctions taking place within 2 days ahead of a short UK auction.

sizable: if the leverage ratio falls by 1 percentage point, banks offer an additional £20mn into the auction. Turning to the other regulatory ratios, the coefficient on the liquidity coverage ratio is insignificant and the coefficient on the Tier 1 capital ratio is statistically significant only for the willingness-to-sell, indicating that dealers with a higher capital ratio have a higher willingness-to-sell. Better capitalized banks have a higher capacity to take on more risk and may be willing to sell gilts in order to raise funds for pursuing profitable risky investments. We also investigate if the effect of the leverage ratio differs at quarter ends, when banks 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 27 in the Online Appendix). When estimated separately for the different maturity buckets (Tables 6-8 in the Online Appendix), a higher leverage ratio is still associated with a lower offer amount but that effect is only marginally statistically significant.

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

Previous work has measured the costs of QE relying on observable auction outcomes such as dealer profits (Song and Zhu (2018), Bonaldi et al. (2015)) or the "round trip cost" of issuing a gilt in the primary market and subsequently repurchasing it in a reverse auction (Breedon (2018)). Our measure of the cost of QE, the weighted average accepted yield (WAAY) spread, is also based solely on observable auction outcomes. The WAAY spread is defined as the weighted average accepted yield relative to the market mid at auction close. Intuitively, this variable is thus the lower bound on the extra profit dealers pocket by forgoing having to transact at the secondary market, since not only are they getting a better price, but they also avoid adverse price effects caused by large trades. Assuming no price impact, the WAAY spread would correspond to the cost of running the auction: the central bank would essentially purchase securities at a lower yield than it could have in the secondary market, thus subsidizing the dealers exactly by that amount.

On average across all auctions, the WAAY spread was -0.34 bps. Since the WAAY spread is in terms of yields, a negative spread essentially corresponds to dealer profits: dealers sold the securities in the auctions at prices that are higher than those on the secondary market. It ranges from 0.1bps for short gilts to -0.5bps for long gilts (Panel (a) of Figure 4), indicating that dealers are "making money" (albeit small) on selling medium and long duration bonds in the auction, but losing on short-duration ones.[19] A potential explanation for this observed pattern is interest rate risk: towards 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 bonds 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. One possible explanation for the observation that dealers are losing money when selling short-dated gilts to the BoE 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. Panel (b) of Figure 4 reports how the WAAY spread varied across time. QE1 recorded the highest cost for the BoE with a WAAY spread of over -0.6bps, while that cost was essentially zero during QE3.

Overall, the cost of QE for the BoE is relatively 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)), suggesting that the benefits of QE outweigh its cost. There are a variety of potential transmission channels through which asset purchases affect spending and inflation, including policy signaling, portfolio rebalancing and improving liquidity in potentially dysfunctional secondary markets (Joyce et al. (2011)). By participating in the auctions and by trading in the secondary market, dealers are actively facilitating the transmission of QE, perhaps justifying a small profit.

Our estimates of the cost of QE are smaller compared to previous research. For example, measuring the cost of QE during QE1 and QE2 by comparing average

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

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 that our ours, which can be explained by the fact that Breedon (2018) uses end of day yields as a comparison, while we compare average accepted yields to yields prevailing in the secondary market at auction close. In our view, the relatively large cost figures in Breedon (2018) are thus at least in part explained by news arriving after auction close and are therefore unrelated to the auction itself.

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, our structural estimation allows us to estimate expected rents that the dealers accrue from participating in the auction as opposed to transacting at the secondary market prices. Such secondary market trades could involve a price impact that might erase these rents altogether. 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 eliminate these rents fully due to the usual private information rents. Hence, these expected rents should not be interpreted directly as the cost of running the QE through the particular mechanism the Bank of England is using. Formally, the implied rents correspond to (the integral of) the strategic effect shown in equation (2).

One possible interpretation of these rents is that they can be viewed as costs of reducing volatility in the gilt market and providing liquidity help to dealers in an anonymous way through the auction. If we were to think about optimal mechanism design, i.e., the problem of how to allocate a given amount of central bank reserves among primary dealers in exchange for securities in their portfolios so that we minimize the cost (measured by spreads relative to the secondary market price), these numbers together with potential efficiency costs of running the auction would constitute the maximal potential savings we could achieve. This upper bound, however, would not be attainable due to the usual rents stemming from dealers having private information.[20]

Compared to the WAAY spread, the rent per bidder (i.e., the transacted quantity-

[20]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.

weighted difference between the maximum yield a bidder is willing to accept and the accepted yield) is with 2.6bps on average much larger. This suggests that in absence of auctions dealers would need to face substantial price impact if they needed to raise liquidity on the secondary market (if they were indifferent, there would be no rents). So prices would be much more volatile and the financial markets would likely face much more uncertainty than with the QE auctions in place. Panel (a) of Figure 5 depicts the split by the maturity bucket. It illustrates that the largest rents accrue on the long maturity buckets - and it is almost 3 bps. Panel (b) of Figure 5 shows how these rents evolved through the various QE waves. The pattern is quite clear: the largest rent from transacting in the auction accrued to bidders in QE1, and it fell steadily through the subsequent waves of QE.

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

$$\mathrm{Y}_{a,b,d} = \alpha_a + \mu_b, + \delta_d + \beta' Z_{a,b,d} + \delta' X_{a,b} + \epsilon_{a,b,d} \tag{4}$$

where $\mathrm{Y}_{a,b,d}$ is either the WAAY spread or estimated rents and $Z_{a,b,d}$ is a vector of variables of interest that measure interest rate risk. $Z_{a,b,d}$ also includes variables related to bidding behavior including the maximal offer amount, number of bids by bond and the dispersion of winning bids. $X_{a,b}$ is a vector of bond-specific controls including the free float, duration, and the pre-auction yield change from the end of the previous day to the end of the auction. Table 6 provides some summary statistics for the regression variables not introduced thus far. Finally, $\alpha_a, \mu_b, \delta_d$ are auction, bond, and dealer fixed effects, respectively.

Table 11 reports the estimation results for both the WAAY spread and estimated rents. As above, we estimate separate regressions for interest rate risk bought and sold and traded volumes, with results for the former being reported in columns (1) and (2) and for the latter in columns (3) and (4). We find that interest rate risk and traded volume do not have a significant effect on either the WAAY spread or rents. This implies that, on average, participating dealers do not increase their profits or rents earned in the BoE's auctions by strategically trading in the secondary market ahead of the auction.

Turning to the other variables in the regression, we find that dealers offering a larger maximum amount also offer a higher yield or lower price relative to the market price prevailing at auction close, reducing the cost of QE. Specifically, for the average maximum offer amount of £40mn, the WAAY spread increases by 0.04bps. 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, and this may be a cheaper way for dealers to offload large positions if the price impact in the secondary market is expected to be high. Similarly, an increase in the maximum offer amount reduces the rent, which declines by 0.4 basis points for the average maximum offer amount, or almost one bid-offer spread. The cover ratio coefficient is negative and highly statistically significant in all regressions, implying that better covered auction reduce the rents, but increase the cost of QE when measured by the WAAY spread. We find a small positive impact of steps within a bond on rents, but statistically insignificant. The number of bids per dealer is, on the other hand, significantly negatively associated with the obtained rents. These two results together suggest that dealers submitting higher number of bids are more diversified (they are offering multiple gilts) and hence they would be able to avoid large price impact in the secondary market if they were unsuccessful in the auction. Therefore, their expected rents from participating in the auction are relatively smaller than less diversified dealers.

7 Conclusions

In this paper, we study the QE auctions implemented in the UK over the past decade. Using data on both winning and losing bids, we use an equilibrium model of bidding to obtain the willingness-to-sell that rationalize the observed offers and use these in our empirical analysis of bidding behavior and the cost of QE.

We document that the realized cost of QE auctions to the BoE is relatively small with only 0.3bps, in particular when compared with the ultimate benefit of the asset purchases to promote price stability in the UK (Joyce et al. (2011)). 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, our structural estimation allows us to estimate the implied rents that the dealers accrue from participating in the auction. On average, these rents are 2.6bps, which is sizable as by participating in the auction, dealers do not need to face the price impact in case they needed to raise liquidity and sell their gilts in the secondary market. So the QE auctions may act as a mechanism that lowers price volatility in the gilt market.

In addition, we show that dealers' willingness-to-sell and the amount offered varies significantly with the amount of interest rate risk acquired in the secondary gilt market prior to the auction and with dealers' regulatory capital. Our results thus indicate that dealers' balance sheet constraints and regulatory incentives play an important role in determining bidding behavior in QE auctions in the UK.

While there is not much a central bank can do about how dealers trade in the secondary market and hence the interest risk they bring to the auction, our results suggest that can be instructive to monitor secondary market activity to better understand the offers received during an auction and perhaps to avoid uncovered auctions. In addition, when designing asset purchases, central banks should consider how regulations affecting dealers' balance sheet capacity may potentially limit the ability of these operations to achieve monetary policy objectives.

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Table 1: QE phases in the UK.

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 2: Residual maturity buckets in UK 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 3: UK and US primary dealers between March 2009 and March 2017.

UK	US
Banco Santander SA, London Branch	
Barclays Bank Plc	**Barclays Capital Inc.**
BNP Paribas (London Branch)	**BNP Paribas Securities Corp.**
	BMO Capital Markets Corp.
	Cabrera Capital Markets LLC
	Cantor Fitzgerald & Co.
Citigroup Global Markets Limited	**Citigroup Global Markets Inc.**
Credit Suisse	**Credit Suisse Securities (USA) LLC**
	Daiwa Capital Markets America Inc.
Deutsche Bank AG (London Branch)	**Deutsche Bank Securities Inc.**
Goldman Sachs International Bank	**Goldman, Sachs & Co.**
	G.X. Clarke & Co.
HSBC Bank Plc	**HSBC Securities (USA) Inc.**
Jefferies International Limited	**Jefferies & Company Inc.**
J.P. Morgan Securities Plc	**J.P. Morgan Securities Inc.**
Lloyds Bank Corporate Markets Plc	
	Loop Capital Market LLC
Merrill Lynch International	**Merrill Lynch, Pierce, Fenner & Smith Inc.**
	MF Global Inc.
	Mischler Financial Group Inc.
	Mizuho Securities USA Inc.
Morgan Stanley & Co. International Plc	**Morgan Stanley & Co. Inc.**
Nomura International Plc	**Nomura Securities International Inc.**
Royal Bank of Canada Europe Limited	**RBC Capital Markets Inc.**
Royal Bank of Scotland Plc	
Scotiabank Europe Plc	**Bank of Nova Scotia, New York Agency**
Societe Generale (London Branch)	**SG Americas Securities LLC**
State Street Bank Europe	
Toronto-Dominion Bank (London Branch)	**TD Securities (USA) LLC**
UBS Limited	**UBS Securities LLC**
Winterflood Securities Limited	

Sources: UK Debt Management Office (UK Debt Management Office (2020)) and Federal Reserve Bank of New York (Federal Reserve Bank New York (2020)).

Table 4: Descriptive statistics for the UK QE reverse auction data

		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
# bonds 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
Offered per bond (£mn)	All	481.5	736.5	396.8	295.3	313.7	494.1
	S	422.1	548.4	452.4	310.2	373.3	410.5
	M	700.7	930.9	484.6	434.5	427.7	924.2
	L	309.9	623.2	253.5	142.1	140.2	147.5
Purchased per bond (£mn)	All	214.5	323.5	204.1	130.3	154.8	190.2
	S	202.7	252.0	243.0	156.0	170.1	181.2
	M	266.1	362.8	224.7	160.3	202.2	276.7
	L	172.2	316.0	144.7	76.2	91.9	112.8
Purch. per win. offer (£mn)	All	48.28	47.41	44.49	41.86	30.23	68.25
	S	57.76	61.28	61.84	54.35	34.55	68.26
	M	48.79	48.86	40.16	44.06	31.54	70.82
	L	39.89	39.54	31.45	27.89	24.59	65.67
Cover ratio	All	2.69	2.62	2.42	2.64	2.27	3.31
	S	3.01	3.47	2.84	2.53	2.66	3.37
	M	2.87	2.75	2.40	3.09	2.31	3.69
	L	2.24	2.10	2.01	2.30	1.84	2.87
WAAY spread (bps)	All	-0.34	-0.65	-0.15	0.00	-0.18	-0.43
	S	0.11	0.36	0.27	0.14	-0.11	-0.14
	M	-0.39	-0.61	-0.31	-0.22	-0.24	-0.20
	L	-0.53	-0.87	-0.32	0.06	-0.17	-0.74
Willingness to sell (bps)	All	0.23	0.49	0.66	0.35	0.68	-1.14
	S	-0.08	-0.13	0.55	0.29	0.28	-1.55
	M	0.02	-0.06	0.63	0.23	0.73	-1.27
	L	0.60	1.23	0.80	0.47	0.97	-0.78

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 1). S, M, L stand for the short, medium and long maturity sector, respectively (Table 2).

Table 5: Mean values for participating dealers' secondary market trading.

	Allocated gilts	Offered gilts	Eligible gilts	Ineligible gilts
Volume bought (GBP mn)	94.27	93.94	43.00	43.00
Volume sold (GBP mn)	84.55	86.88	42.77	43.73
Interest rate risk bought (GBP mn)	1216.71	1170.38	555.88	475.81
Interest rate risk sold (GBP mn)	1083.91	1081.67	550.00	481.49

Notes: The Table reports averages for both interest rate risk and traded volumes accummulated by dealer and bond over 2.5 days ahead of each auction.

Table 6: Descriptive statistics

Statistic	Mean	Median	Min	Max	St. Dev.
		Bond characteristics			
Free float (GPB mn)	22,589.97	23,452.00	2,500.00	36,025.00	7,459.07
DV01 (GBP per bps change in yield)	10.59	6.41	0.003	62.23	11.19
Pre-auction yield change (bps)	−1.06	−0.80	−15.10	15.90	3.64
		Additional UK QE reverse auction variables			
Max. offer amount (GPB mn)	40.06	25.00	5.00	1,016.00	65.26
No. bids per dealer	2.01	1.86	1.00	6.83	0.91
No. bids per bond	2.23	2.00	1.00	27.00	1.49
Dispersion of winning bids	0.04	0.01	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
		US QE (reverse) auction variables			
Interest risk of bonds bought from the Fed (USD mn)	89.52	0	0	9,542	546.41
Interest risk of bonds sold to the Fed (USD mn)	1,427.24	0	0	47,659	3,596.82
Amount of bonds bought from the Fed (USD mn)	52.40	0	0	5,460	296.60
Amount of bonds sold to the Fed (USD mn)	116.39	0	0	5,264	361.11

Notes: Data on bond characteristics is from the UK Debt Management Office, BoE and Bloomberg. Regulatory returns are from S&P Global Market Intelligence and are available at quarterly frequency. Data on US QE auctions are from the Federal Reserve Board and use US QE auctions within 2 days ahead of a UK QE auctions. US auction data are aggregated at the dealer level.

Table 7: Summary statistics for the US QE auction data.

		Purchases	Sales
# auctions		710	75
# bonds per auction		13.17	12.00
# dealers per auction		14.70	15.68
amount purchased/sold:	total ($mn)	2,424,230.01	640,882.83
	per auction ($mn)	3,414.41	8,545.09
cover ratio		3.803	8.001
residual maturity		15.07	1.824

Table 8: Participant's offering behavior in UK QE reverse auction and domestic interest rate risk

	Willingness-to-sell	Offer yield	Offer amount	Willingness-to-sell	Offer yield	Offer amount
Interest rate risk bought (GPB bn)	0.10	0.05	0.01***			
	(0.06)	(0.05)	(0.001)			
Interest rate risk sold (GPB bn)	−0.17***	−0.06	−0.001*			
	(0.05)	(0.06)	(0.001)			
Volume bought (GPB bn)				1.01	0.63	0.10***
				(0.67)	(0.72)	(0.02)
Volume sold (GPB bn)				−1.61**	−0.27	−0.03**
				(0.77)	(0.88)	(0.01)
DV01	−0.01	−1.16***	−0.0003*	−0.01	−1.16***	−0.0001
	(0.04)	(0.20)	(0.0002)	(0.04)	(0.20)	(0.0001)
Free float (GPB bn)	−0.05*	−0.21*	−0.0001	−0.05*	−0.21*	−0.0001
	(0.03)	(0.10)	(0.0002)	(0.03)	(0.10)	(0.0002)
Pre-auction yield change (bps)	0.06	1.26***	0.002***	0.06	1.26***	0.002***
	(0.10)	(0.20)	(0.001)	(0.10)	(0.20)	(0.001)
Bond 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	10,637	10,637	47,863	10,637	10,637	47,863

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

Notes: The Table reports estimation results from equation (3). Standard errors are clustered by bond. Willingness-to-sell and offer yield are in bps, and offer amount is in £ bn. Regressions with willingness-to-sell or offer yield as the dependent variable use all gilts that have been offered to sell in a particular auction and regressions with offer amount as the dependent variable uses all eligible gilts in a particular auction.

Table 9: Participant's offering behavior in UK QE reverse auction and UK and US interest rate risk

	Willingness-to-sell	Offer yield	Offer amount	Willingness-to-sell	Offer yield	Offer amount
Interest rate risk bought (GPB bn)	−0.002	−0.10	0.01***			
	(0.06)	(0.06)	(0.002)			
Interest rate risk sold (GPB bn)	−0.03	−0.001	−0.001			
	(0.04)	(0.06)	(0.001)			
Volume bought (GPB bn)				−0.12	−1.06	0.09***
				(0.88)	(0.91)	(0.03)
Volume sold (GPB bn)				−0.31	−0.53	−0.02
				(0.68)	(0.68)	(0.02)
DV01	0.31*	−2.82	−0.0003	0.31*	−2.83	−0.0003
	(0.16)	(1.90)	(0.001)	(0.16)	(1.90)	(0.001)
Free float (GPB bn)	0.01	−0.18	−0.0002	0.01	−0.17	−0.0002
	(0.02)	(0.13)	(0.0002)	(0.02)	(0.13)	(0.0002)
Pre-auction yield change (bps)	−0.02	1.21***	0.002**	−0.02	1.21***	0.002***
	(0.10)	(0.24)	(0.001)	(0.10)	(0.24)	(0.001)
Interest rate risk of bonds bought from the Fed (USD bn)	−0.04	0.01	−0.0003			
	(0.07)	(0.09)	(0.001)			
Interest rate risk of bonds sold to the Fed (USD bn)	0.003	−0.003	0.0004*			
	(0.02)	(0.02)	(0.0002)			
Amount of bonds bought from the Fed (USD bn)				−0.07	−0.06	−0.001
				(0.12)	(0.18)	(0.001)
Amount of bonds sold to the Fed (USD bn)				0.02	−0.001	0.004*
				(0.16)	(0.20)	(0.002)
Bond 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	46	46	46	46	46	46
Observations	5,115	5,115	21,978	5,115	5,115	21,978
Note:						*p<0.1; **p<0.05; ***p<0.01

Notes: The Table reports estimation results from equation (3). Standard errors are clustered by bond. Willingness-to-sell and offer yield are in bps, and offer amount is in £ bn. Regressions with willingness-to-sell or offer yield as the dependent variable use all gilts that have been offered to sell in a particular auction and regressions with offer amount as the dependent variable uses all eligible gilts in a particular auction. The sample is resitricted to common primary dealers in the UK and US and to US QE 3 and the Maturity Extension Programme.

Table 10: Participant's offering behavior in UK QE reverse auction and regulatory constraints

	Willingness-to-sell	Offer yield	Offer amount	Willingness-to-sell	Offer yield	Offer amount
Interest rate risk bought (GPB bn)	0.20	0.14	0.01***			
	(0.14)	(0.12)	(0.002)			
Interest rate risk sold (GPB bn)	−0.53***	−0.47***	0.002			
	(0.10)	(0.08)	(0.001)			
Volume bought (GPB bn)				1.90	0.91	0.17***
				(1.91)	(2.00)	(0.03)
Volume sold (GPB bn)				−6.78**	−5.60**	0.02
				(2.65)	(2.63)	(0.03)
DV01	0.23*	0.59**	0.002	0.24*	0.60**	0.002
	(0.12)	(0.24)	(0.001)	(0.13)	(0.25)	(0.001)
Free float (GPB bn)	−0.68***	−0.07	0.01***	−0.67***	−0.06	0.01***
	(0.09)	(0.17)	(0.003)	(0.10)	(0.16)	(0.002)
Pre-auction yield change (bps)	−0.74*	1.84***	0.004	−0.71*	1.87***	0.003
	(0.42)	(0.57)	(0.003)	(0.42)	(0.57)	(0.002)
Leverage ratio (percent)	1.19	2.86**	−0.02**	1.11	2.78**	−0.02**
	(1.13)	(1.23)	(0.01)	(1.14)	(1.22)	(0.01)
Liquidity cov. ratio (percent)	−0.03	0.003	−0.0002	−0.03	0.01	−0.0002
	(0.03)	(0.03)	(0.0002)	(0.03)	(0.03)	(0.0002)
Tier one capital ratio (percent)	1.33*	0.93	−0.004	1.43*	1.02	−0.005
	(0.73)	(0.70)	(0.005)	(0.72)	(0.69)	(0.004)
Bond 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	1,139	1,139	4,818	1,139	1,139	4,818

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

Notes: The Table reports estimation results from equation (3). Standard errors are clustered by bond. Willingness-to-sell and offer yield are in bps, and offer amount is in £ bn. Regressions with willingness-to-sell or offer yield as the dependent variable use all gilts that have been offered to sell in a particular auction and regressions with offer amount as the dependent variable uses all eligible gilts in a particular auction. 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) and to dealers where regulatory returns are available.

Table 11: The cost of UK QE reverse auction, participant's rents, their offering behavior and secondary market trading

	WAAY spread	Rent	WAAY spread	Rent
Interest rate risk bought (GPB bn)	−0.005	−0.01		
	(0.01)	(0.06)		
Interest rate risk sold (GPB bn)	0.0003	−0.06		
	(0.01)	(0.07)		
Volume bought (GPB bn)			−0.02	−0.21
			(0.07)	(1.01)
Volume sold (GPB bn)			−0.05	−0.09
			(0.06)	(0.90)
DV01	0.01	0.02	0.01	0.02
	(0.01)	(0.02)	(0.01)	(0.02)
Free float (GPB mn)	−0.001	−0.02	−0.001	−0.02
	(0.002)	(0.02)	(0.002)	(0.02)
Pre-auction yield change (bps)	−0.01	−0.08	−0.01	−0.08
	(0.01)	(0.08)	(0.01)	(0.08)
Max. offer amount (GPB mn)	0.001***	−0.01***	0.001***	−0.01***
	(0.0001)	(0.004)	(0.0001)	(0.004)
Cover ratio by bond	−0.002***	−0.02***	−0.002***	−0.02***
	(0.0005)	(0.01)	(0.0005)	(0.01)
Offer amount by bond	−0.0000	−0.0002	−0.0000	−0.0002
	(0.0000)	(0.0003)	(0.0000)	(0.0003)
No. bids per dealer	−0.01	−0.36***	−0.01	−0.37***
	(0.01)	(0.09)	(0.01)	(0.09)
No. bids per bond	0.002	0.07	0.002	0.07
	(0.004)	(0.06)	(0.004)	(0.06)
Dipersion of winning bids	−0.45	0.70	−0.46	0.64
	(0.33)	(1.03)	(0.33)	(1.01)
Bond FE	Yes	Yes	Yes	Yes
Auction FE	Yes	Yes	Yes	Yes
Dealer FE	Yes	Yes	Yes	Yes
No. auctions	260	260	260	260
Observations	5,581	5,581	5,581	5,581
Note:				*p<0.1; **p<0.05; ***p<0.01

Notes: The Table reports estimation results from equation (4). Standard errors are clustered by bond. WAAY spread is the weighted average accepted yield relative to the market yield at auction close. The rent is measured as the surplus accruing to dealers from participating in the auctions. WAAY spreads and rents are expressed in bps.

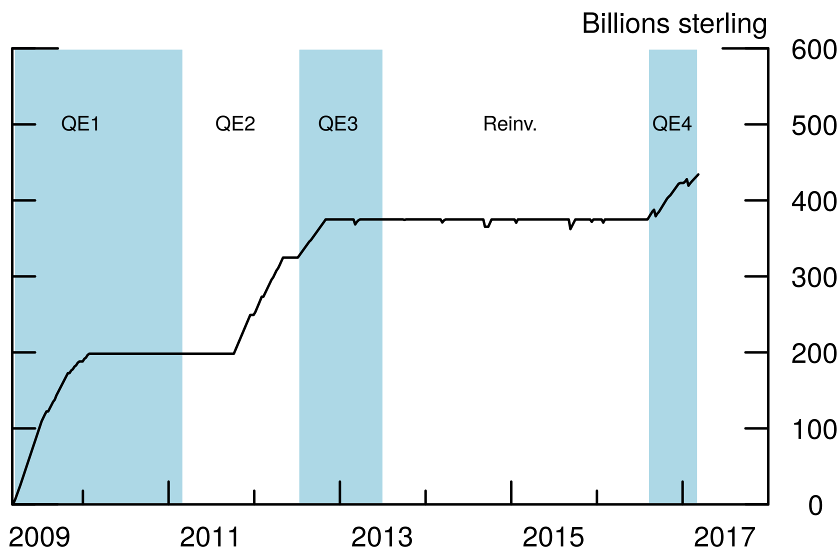


Figure 1: Stock of gilts held by the APF in £bn.

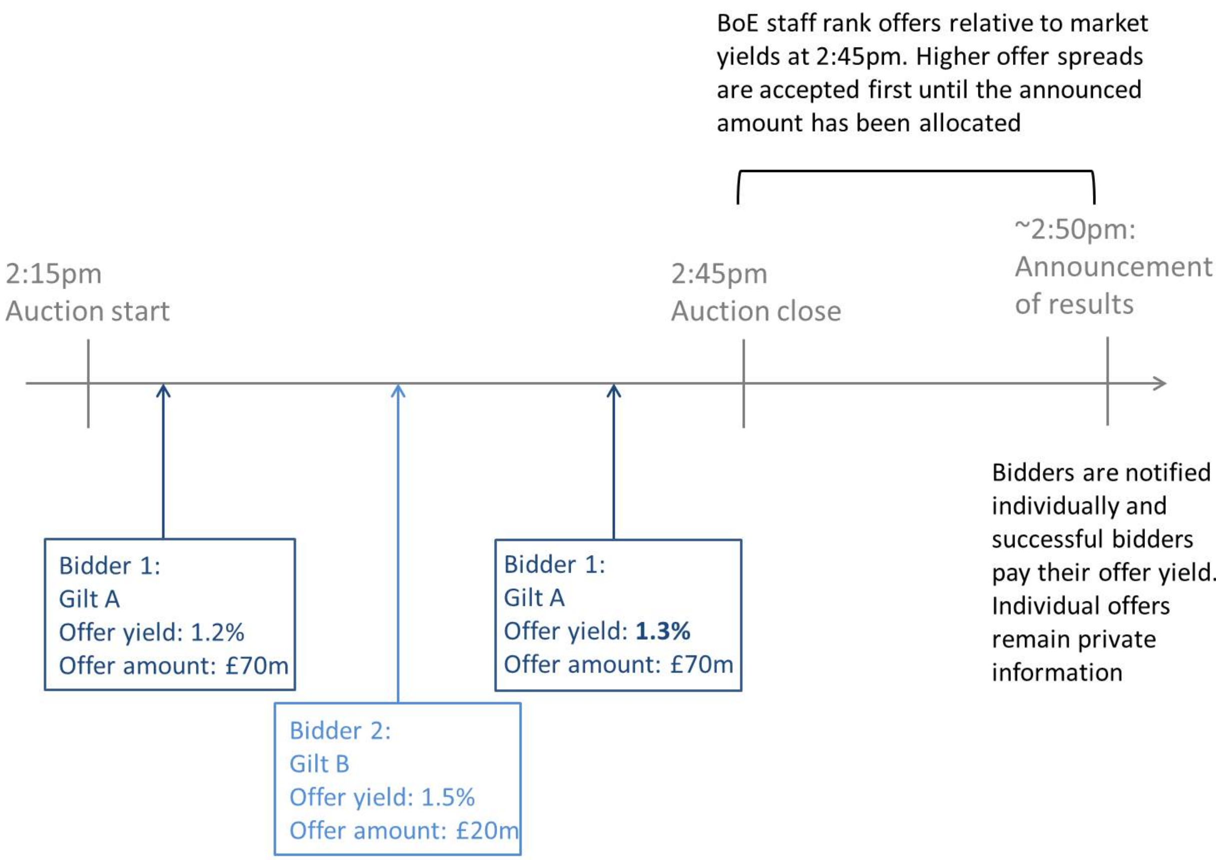
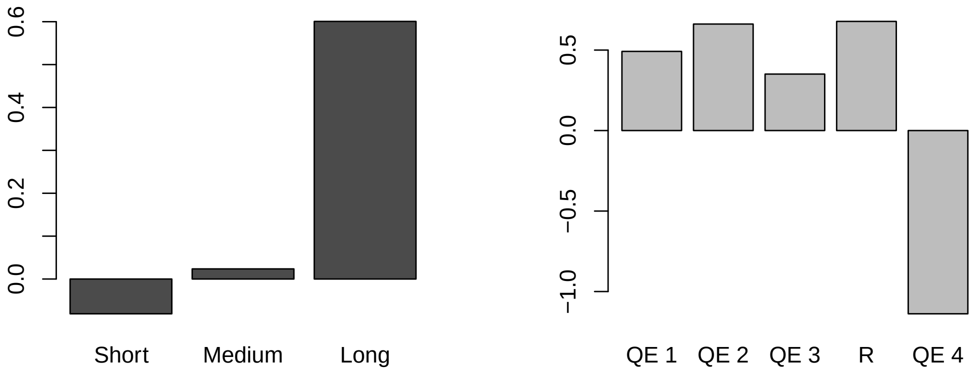
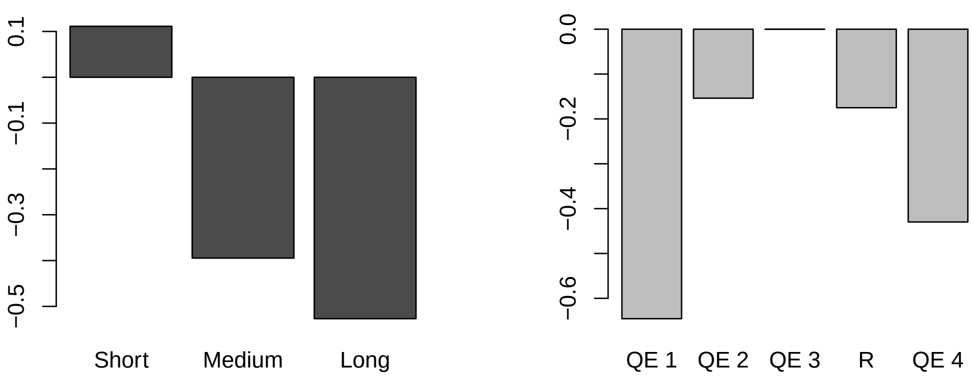


Figure 2: Time line of a typical QE auction at the BoE.



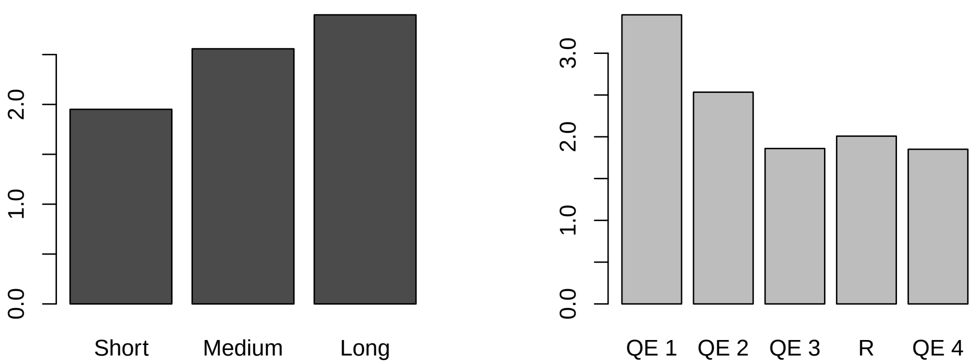
(a) by maturity bucket (b) by QE phase

Figure 3: Willingness to sell (bps).



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

Figure 4: Weighted average accepted spread (bps).



(a) by maturity bucket

(b) by QE phase

Figure 5: Rents (bps).