Funding Quantitative Easing to Target Inflation*

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Abstract

The study of quantitative easing (QE) policies has so far focussed on which assets the central bank should buy, and on how it can pursue its targets for real and financial stability. This paper emphasizes instead the funding of QE by central bank liabilities, with an eye on achieving the inflation target. Looking backwards, it shows evidence that post-QE1, the U.S. banking sector became saturated with reserves, so the central bank can control the size of the balance sheet independently of its interest-rate policy. Using options data for U.S. inflation, it shows that while QE1 had an effect on expected inflation, further rounds of QE did not. Looking forward, it estimates the feasibility of keeping the liabilities of the central bank at a high level in terms of a solvency upper bound. Finally, it argues that the central bank's interest-rate policy is not out of ammunition when it comes to targeting inflation, since there are radical proposals on the composition of its liabilities, their maturity and the way to remunerate them that could be employed.

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I Introduction

Quantitative easing (QE) refers to a set of monetary policies that expand the size of the balance sheet of the central bank by purchasing government bonds, and funds it by issuing monetary base. It started on a large scale in Japan in March of 2001 and was later adopted, between 2008 and 2009, by the other three major central banks. Even though they all initially stated that QE was a temporary measure, the size of their balance sheets in 2016 is as large as ever, and both the ECB and the Bank of Japan have suggested expanding QE further. The central-bank balance sheet has become an active policy tool.

Not so long ago, discussion of a new monetary policy tool would have been dominated by its implications for the supply of money, for nominal interest rates, and for inflation. Yet, in recent years, research and discussions have instead emphasized what QE implies for real and financial stability, and they have focussed on what central banks buy, at what price, to sell when. This shift is understandable and perhaps desirable, in response to dismal economic growth in developed economies and to the long-lasting ripples of a financial crisis. Moreover, it has paid off in terms of a better understanding of the effects on the economy and financial markets of different types of publicly-funded asset purchases.[1]

Figure 1 shows the balance sheet of four major central banks over the past 10 years, after some effort to consolidate and harmonize items into common categories that is explained in the appendix. Above the horizontal axis is the asset side of the balance sheet. Of particular research attention over the past few years have been: the Federal Reserve's 2008 growth and quick elimination of "Others" as a result of its unconventional policies; the ECB's increase in direct holding of securities; the Bank of England's funding a separate vehicle, the Asset Purchase Facility, to buy gilts with an indemnity from the fiscal authorities; and the Bank of Japan's large increase of long-term government bond holdings past 2010, making its balance sheet more than twice as large as that of the other three banks. In these discussions,

when the liabilities side was mentioned, it often came with vague mentions of "printing money". Inflation concerns were swept to the side by noting that long-term mean inflation expectations remained anchored and on target. This paper's goal is to shift attention back to the other side of the balance sheet, and back to the other leg of the dual mandate.[2]

Starting with the central-banks' liabilities, figure 1 shows that in contrast with the variety on the asset side, the change in the balance sheet of these four central banks looks the same on the liabilities side. All four financed their purchases via overnight interest-paying voluntarily-held deposits by financial institutions at the central bank. I will call these reserves for short. This uniform development is remarkable on several accounts. First, from the perspective of history, this liability was minor in these central banks before 2007, and did not even exist in the Federal Reserve, since the Fed had no legal authority to pay interest on reserves. Second, from the perspective of economics, many textbooks still refer to reserves and currency as interchangeable parts of the monetary base, when in fact their time-series correlation is close to zero. Third, from the perspective of the holders of reserves, in 2007, U.S. banks held slightly more securities issued by the Treasury than they held reserves at the central bank; by the end of 2015, banks held twice more reserves than Treasuries. Fourth, from the perspective of financial markets, the value of reserves is higher than the outstanding amount of almost any security with a common issuer and common maturity in these four economic regions. Finally, from the perspective of monetary policy, the central bank can choose both the quantity of nominal reserves as well as the interest at which to remunerate them.

Turning attention to the other leg of the dual mandate, figure 2 evaluates how these four major central banks have performed with respect to their inflation goal. The figure is constructed as follows. For each central bank, the log price index is set at zero the last time the mandate of the central bank was reset. All four central banks have a target of 2% annual change in the price level, set up at different dates, so a dashed line is drawn forward in time to represent the actual target, and circles are drawn moving backwards in time to capture

an hypothetical target. The actual price level is then superimposed, using data on the index that the mandate refers to, and normalizing to equal the target in the year the mandate was announced. Therefore, at every date, each chart in figure 2 reports how far is the central bank from the ideal price-level target.[3]

The ECB has been the closest to the ideal price-level target, while the Bank of England was the furthest in 2015 after successive deviations following the financial crisis. Both the Federal Reserve and the Bank of Japan have been close to the target since their 2012 and 2013 mandates, respectively, but the performance of the U.S. price level for more than a decade before was also very close to the hypothetical target, while the BoJ was quite far. Overall, central banks were successful in the past. In the future, there is reason for concern. Both in the Eurosystem and United States, since 2014 the price level has been increasingly below target, and the same is true from 2015 onwards for the Japan and the United Kingdom. Forecasts of inflation over the next 2-3 years for all regions, from either surveys or financial markets, do not show any signs of a correction upwards. Therefore, by current estimates, all but the United Kingdom are expected to be below target by at least 6% by 2019.

This downside risk justifies moving attention back to inflation and away from the recent focus on financial and real stability. Since reserves are the unit of account in the economy, inflation is by definition the change in the real value of reserves. If there is some link, even if tenuous, between the size of central-bank liabilities and the price level, then changes in the funding side of QE should affect inflation. Therefore, from an inflation perspective, one would like to consider the effect of keeping the current size of the central-bank balance sheet, or perhaps expanding it through further QE.

This paper discusses the funding side of QE and its implications for inflation. It provides a central-bank liability-theory of QE to complement existing asset-theories of QE, presents some evidence in favor of it, and discusses its policy implications. Throughout, it analyses the type and size of reserves that are issued as part of QE policies, and their expected effects

on the price level. This leads to four conclusions, one in each of the sections that follows. First, section II argues that the market for bank reserves in the United States has been saturated since about 2011. Theoretically, post-QE the supply of reserves shifted far enough to the right that it now intersects the demand curve at its horizontal segment. Empirically, bank-level data on assets shows how QE significantly changed the distribution of reserves deposits by banks. Second, section III makes the case that once the economy is saturated, only the interest paid on reserves but not the size of the balance sheet have an effect on inflation, so they can be used as independent policy tools. Using data on inflation options to perform an event-study analysis of the effects of QE on inflation, it shows that the first round of QE shifted the distribution of expected inflation. But, consistent with the theory, since QE2, further expansions of the balance sheet have had little to no effect on inflation expectations across their entire distributions. Third, section IV asks whether keeping the current elevated size of the central bank's balance sheet, or even engaging in further QE, is feasible. Keeping the focus on liabilities and inflation, it discusses the constraint posed by the solvency of the central bank in terms of a solvency upper bound on the size of QE. The United States in 2016 is well below this bound. Fourth, section V argues that the central bank is not out of firepower to affect inflation, even if it focuses solely on reserves and their remuneration. It discusses three radical proposals for innovating on the future composition of QE, in case inflation starts deviating significantly from target. The first replaces reserves by currency, often called "helicopter drops". The second uses reserves that have payments indexed to the price level. The third issues medium-term reserves with promised future interest rates.

Finally, section VI concludes by drawing the link between the needed new study of reserves and the old study of monetary aggregates. This paper's conservative message for inflation-targeting in the future is to return to the pre-crisis consensus of following rules for interest rates and communicating present and future changes in the interest-rate path,

leaving QE aside to potentially deal with other goals. Three changes to this old consensus are proposed. First, that the main target interest rate in the United States stops being the Federal Funds rate and becomes the interest on reserves. Second, that the return to a lean Fed balance sheet does not go all the way back to the pre-crisis zero reserves, but keeps the market for reserves saturated. Third, that if radical policies are needed to bring inflation back on target, these take the form of innovations on the composition of the central-bank liabilities that keep the focus on the return on the reserves that the central bank can control.

II An economy saturated with reserves

Reserves are one of the many financial assets that banks can choose to hold. A bank with a positive balance of reserves at the central bank can use it to pay for securities or to settle credits from another bank, and in doing so adjust the share of reserves in its overall portfolio. Moreover, the bank can request that the central bank exchanges its reserves for currency at any time and purchase goods and services with the banknotes, converting this form of savings into expenditure. In many regards, reserves are not all that different from overnight loans to other financial institutions or even from short-term government bonds.

At the same time, the history of reserves is special. The Federal Reserve was founded in 1913 partly as a response to frequent financial crises that led to mistrust in existing payment systems. Because banks issue means of payment, every hour the credits over one bank are used to pay debits to another bank. These must be very regularly settled in a clearing house, using either currency or some other clearing-house means of payment. Since an individual bank's financial health is private information to its managers, a successful clearing house has to constantly monitor its participants, as well as keep its own managers in check from the temptation to over-print house money. The Federal Reserve as a public institution was set up to solve both problems, by being given broad powers to regulate banks and, crucially, the

mandate to issue the house means of payment that all banks would accept to settle interbank claims: reserves.

Because of this unique role, reserves have two properties that are not shared with other financial assets. First, the central bank is the monopoly issuer of reserves. To support this function, central banks were also given the power to issue banknotes that are legal tender and which can be exchanged for reserves at a one-to-one exchange rate.[4] Therefore, reserves are the unit of account in the economy: they define the price level as the inverse of the real value of reserves. As the monopoly issuer or the unit of account, the central bank can freely choose which interest to pay on these reserves. It can always honor this promise by issuing more reserves.

Second, only banks can hold reserves. This implies that, because the market for reserves must clear, the aggregate amount of reserves in the overall banking system plus banknotes is determined by the central bank. The central bank perfectly controls their sum, even if it does not control the breakdown between the two components of the monetary base, nor the distribution of reserves across banks.

These two properties combined imply that the central bank can in principle choose both the quantity of the monetary base and the nominal interest rate paid on reserves. Whether it can also control the quantity of reserves, and do so independently of the interest rate that it pays, depends on the demand for reserves by banks.

II.A The demand for reserves

Figure 3 portrays a fictional market for reserves.[5] The vertical axis has the real price of reserves. While they pay a nominal interest rate that is fixed ex ante by the central bank, their ex post real return also depends on the realization of inflation. In turn, it is the comparison of this return with that of similar assets that determines the relative opportunity cost of investing in reserves instead of these alternatives. The real price of reserves is approximately

equal to the difference between the expected risk-adjusted real return on alternative assets minus that on reserves.

The demand curve is then plotted in figure 3. Central banks usually set a minimum required amount of reserves that banks must hold so that, in all but exceptional days, they can satisfy immediate claims by other banks in the clearing house and obtain banknotes to satisfy deposit withdrawals. As with almost all financial regulation, this is also a form of financial repression, since banks are forced to demand these reserves regardless of their price (or return). The demand for reserves therefore starts as a vertical line at the level v^r. Before QE, the supply curve was very near this level and the market for reserves cleared close to v^r. Required reserves were a tool for financial regulation (and for taxing banks), not for active monetary policy.[6]

A lower price for reserves raises demand up to a level v^s, when the market is satiated. The downward slope reflects the services that reserves may provide in the form of liquidity. The scarcity of this liquidity leads to a premium being priced onto reserves, and the smaller this premium is, the larger the demand for reserves. There is some point though at which banks have all the liquidity they want. Perhaps this happens very quickly when reserves are only a small fraction of bank's portfolios, or perhaps it happens only when there are trillions of reserves outstanding, but in a world with a finite amount of goods and services to buy, the desire for liquidity must have a limit. This is v^s, the point at which the famous Friedman rule is achieved because banks are flooded with all the liquidity they want at no opportunity cost. From that point onwards, the opportunity cost of holding reserves (the liquidity premium) disappears and banks are indifferent towards holding more reserves. No arbitrage takes over so, just as is the case for other liquid financial assets, the demand curve becomes close to horizontal.

Does the supply curve for reserves look vertical, as plotted in the figure, or do banks substitute any supply of reserves for currency? And has QE saturated the banking system

of advanced economies with reserves? The remainder of this section looks for evidence that the United States is in the horizontal segment of the demand curve.

II.B The link between reserves, currency and and interest rates

Figure 4 plots aggregate reserves between 2005 and 2015. The effect of QE jumps to the eye, with the announcements of the three waves of the program leading to quick and sharp increases in reserves issued and held.

The central bank does not perfectly control the amount of reserves because of its commitment to exchange reserves for currency one-to-one at all dates. While QE was implemented by issuing reserves to buy assets, banks could have asked to exchange those reserve balances for banknotes, so that hypothetically the aggregate market-clearing amount of reserves outstanding could have not changed at all. If the zero nominal interest rate paid on reserves were the effective zero lower bound, then private agents would be indifferent between cash and reserves, and the supply curve could take any shape. Figure 4 also plots the banknotes held by banks, but it is barely indistinguishable from the horizontal axis since this is so small relative to both the size of reserves and its change in absolute value after QE. Curiously, the ratio of banknotes to reserves is almost exactly the same in June 2016 as it was in June 2009, at about 0.04. It is possible that banks could have passed on the banknotes to households and firms before answering the survey. Figure 4 therefore also plots all currency in circulation. QE has very little effect on the steady growth of currency, and the spikes in the issuance of reserves barely registered any noticeable tick up in banknotes. To conclude, there was little substitution from reserves to currency even when the interest rate on reserves was zero, so the central bank's reserves issued matches very closely with reserves ultimately outstanding. Portraying the supply of reserves as a vertical line is a good approximation.

If the demand curve is horizontal, then the interest on reserves should be very close to that of similar investments. Even taking away the two special properties of reserves

discussed above, there is no asset with the exact same payoff as reserves in all states of the world. Loans in the Federal Funds market are close, being also denominated in dollars and paying an overnight nominal interest rate, but they have an (even if small) amount of default risk. The same applies to private overnight repos or swaps due to their counterparty risk. Treasury securities are close to as default-free as reserves, but they are issued at maturities longer than overnight. The best that can be done is to look at the interest rates in the Federal Funds market and in 3-month Treasury bills to construct the difference from the interest on reserves as the real price of reserves.

This price will not be precisely zero for at least four reasons. First, because of the differences in maturity and default risk. Second, because only some financial institutions can deposit reserves at the Federal Reserve, only some others can trade in the Federal Funds market, while investing in Treasury bills is open to all. Third, in the case of the Federal Funds rate, because of changes in the liquidity of that market, which have been significant during the years of QE.[7] And fourth, because there may be small fluctuations over time in the expectation of risk-adjusted inflation and in the inflation risk premium due to a covariance between inflation and the interest-rate differences. Therefore, there will be fluctuations in the difference between the interest on reserves, and the interest on federal funds and Treasury bills, but these should have little effect on the demand for reserves, for the demand curve to be effectively flat.

Table 1 takes a first stab at testing this hypothesis. It uses monthly data on reserves from the end of 2011 until June 2016, and regresses it on the two measures of the price of reserves. I consider a variety of specifications that deal differently with the trend in reserves during this period and alternate in the choice of which of the two measures of the price of reserves to consider. The first five specifications reported in the table give the same clear answer. The semi-elasticity of reserves to interest rates is not statistically significantly different from zero, and it is always estimated to be quite small, where for the largest estimate in specification

(5), a one standard deviation increase in the difference between reserves and federal funds rates (of 4 basis points) would lower the demand for reserves by 0.8%. The sample has few observations since the hypothesis is that the market for reserves has only been saturated for less than 5 years, so the results can only be tentative. One check is to see what happens if we go further back and extend the sample until November 2008, when the Federal Reserve started paying interest on reserves. Because this includes a time before QE had expanded the amount of reserves to a significant size, it should include observations when the market was in the downward-sloping range for demand. Indeed, the estimated semi-elasticity in the last column of the table is now two to four times larger than in the other columns and statistically significant.[8]

The data is therefore consistent with QE having pushed the vertical supply for reserves sufficiently to the right so that, from 2011 onwards, the United States has been in the range where the demand for reserves is horizontal. The market for reserves is saturated, and the Fed can independently choose the amount of reserves and their interest rate.

II.C The distribution of the reserves-deposit ratio

These aggregate results may mask a great amount of heterogeneity across banks. It is well known that a few banks hold a very large share of the reserves outstanding; the 10 largest reserve holders had approximately 65% of the entire stock in 2011.[9] Perhaps only a few banks are indeed satiated in their demand for liquidity, and idiosyncratic bank shocks could easily push the market for reserves lack to the left of the satiation point. To investigate this possibility, I turn to bank-level data on reserve deposits.

Three broad types of institutions can hold reserves at the Federal Reserve Banks: commercial banks, savings banks including trust companies and thrifts, and foreign banks or branches that are not covered by deposit insurance. The Federal Reserve's H.3 and H.4.1 statistical releases used in figure 4 report the total reserves, but not their distribution by

holder. However, all of these institutions but for credit unions and a few thrift institutions must report their reserve deposits as part of their quarterly supervisory reports, the Call Reports, with the Federal Financial Institutions Examination Council (FFIEC). I use the end-of-year reports for 2005 and 2007, before QE started, in 2011 by the end of the large QE1 and QE2 programs, and in 2015, the last year in the sample. The data covers approximately 6,000 financial institutions. Aggregating over the bank-level data and comparing to the Fed's aggregate reports, the correlation between the two series is almost perfect, with the bank-level data covering approximately 90% of aggregate reserves holdings. Because these are regulatory filings, they come with a wealth of information on each bank's balance sheet, including size, deposits, and holdings of government securities.

Figure 5 starts by looking at the ratio of reserves to deposits for each individual bank, plotting its cumulative density function at the four dates. Before QE, the many deposit-insured institutions in the sample had to hold a minimum ratio of reserves to deposits. As the distribution for 2005 and 2007 shows, most of them did just that, so that in 2007, the median reserve-deposit ratio was 0.10%, and the interquartile range was a narrow 0.38%. Most institutions had an inelastic demand for reserves, with only a few at the margin holding a large amount of reserves.

Given the enormous increase in total reserves, it is not surprising that the distributions post-QE look dramatically different from those pre-QE. More interesting is that, above the last quartile, the *entire* distribution shifted rightwards. It was not just those previously at the margin that increased their reserves deposits, but the majority of banks started having reserves well in excess of their regulatory requirements. The whole density of banks' reserves shifts right and spreads out. Many more banks are voluntarily choosing to hold reserves at the central bank while taking into account the opportunity cost of doing so. This suggests that many banks are in the horizontal segment of their individual demand curve, willing to hold more reserves if the central bank chooses to issue them.

Table 2 confirms this in a different way, by mapping each bank's reserves-deposit ratio across time, and calculating the correlation across banks. The banks that held a high reserves-deposit ratio in 2005 are not the same that hold higher reserves ten years later: the correlation is a mere 2%. The correlation is likewise very low between reserves-deposits in 2011 and in 2015. Relative to before QE, the current holders of reserves seem to no longer be holding reserves solely to satisfy regulation.

II.D The share of reserves in banks' portfolios

Another way to describe being on the horizontal segment of the demand curve is that reserves are now one of many assets that an individual bank chooses to hold more or less of in its portfolio. With QE, reserves became a regular highly liquid financial asset, with returns pinned down by arbitrage forces rather than by fluctuations in the quantity supplied.

Figure 6 and Table 3 try to confirm this hypothesis by again plotting the distribution across banks and the correlation across time, but now for the ratio of reserves to assets. Post-QE, the portfolio shares are higher both on average and for most banks, with the median rising from 0.07% in 2007 to 2.91% in 2011. Moreover, they are more spread out, as the interquartile range went from 0.29% to 6.51% between 2007 and 2011. This is even more noticeable at the top, where the difference between the 99 and the 90 percentiles of portfolio shares went from 1.25% to 9.92% in just four years.

Yet another way to see the change in the composition of banks' portfolios, and in the distribution of the reserves share across banks, is to compare their reserve deposits with their holdings of Treasury securities. Most U.S. banks hold no Treasuries, and this has not changed with QE. The share of banks holding zero securities barely changed from 79% in 2005 to 78% in 2015, and the share of banks for which Treasury securities are less than 2% of their assets stayed completely unchanged at 94%. Yet, the share of banks that hold more reserves than Treasuries increased significantly from 79% to 90%.

III Does QE raise inflation?

If the supply curve is vertical and to the right of v^s, then the central bank can keep on expanding QE and banks will keep on holding these reserves. At the same time, the central bank no longer controls the real equilibrium price of reserves. What the central bank freely sets, as always, is the nominal interest rate on these reserves. But this is approximately equal to the sum of the expected rate of inflation and the equilibrium real interest rate. In turn, in the short run with nominal rigidities, expected inflation moves little, and the real interest rate depends negatively on current output growth, which depends positively on unexpected inflation. All combined, a permanently higher nominal interest rate on reserves comes with higher inflation (the Fisher effect), while a temporarily higher nominal interest rate on reserves lowers inflation (the Phillips effect). Pinning down precisely by how much, or drawing the exact line between temporary and permanent, is a perennial topic of study in monetary economics, which is particularly complicated because models say that it depends on past and future inflation, on whether the policy change persists, on whether it was unexpected, and on whether it was a reaction to endogenous variables.[10] But the basic point remains: in an economy saturated with reserves, the central bank can freely choose that interest rate on reserves and this pins down inflation.[11]

Before QE started, an increase in reserves would have moved the market for reserves along a downward-sloping demand. The central bank could not independently choose the size of its balance sheet and the target for an overnight interest rate. The two were tied together, so a QE policy was an expansionary monetary policy in the sense of pushing for lower shorter-term interest rates and perhaps higher inflation. If the market for reserves was close to the vertical segment, because the central bank kept the supply of reserves close to the regulatory requirements v^r, then even small changes in the monetary base had large effects on nominal interest rates and from there on inflation and the economy. The size of the

liabilities of the central bank was a measure of the stance of monetary policy, and monetarist proposals for using this size to control inflation were valid.

But once the central bank balance sheet grows large enough, and reserves become larger than v^s, then the size of the central bank's balance sheet is no longer a predictor of inflation. Further QE announcements have no effect on inflation in an economy saturated with reserves. Only announcements about interest rates on reserves, in the present or in the future, allow the central bank to steer inflation towards its target.[12]

The remainder of this section investigates this empirical prediction that the first rounds of QE may have moved inflation, but that once the size of the balance sheet grew past a point, further QE had little effect on prices. Before doing so though, the next subsection takes a short detour to discuss general equilibrium. Readers less interested in theoretical subtleties can skip ahead to the next subsection.

III.A An aside: general-equilibrium effects of QE on real outcomes

So far, this paper has discussed the market for reserves separately from the rest of the economy. The implicit assumption to make this completely valid was that the amount of reserves in the economy did not have an effect on households' choices of consumption and work, or on firms' choices of production or investment. Otherwise, QE might have some direct effect on real activity and real interest rates and, through that channel, on inflation.

This possibility does not invalidate the arguments that were made so far. Even if the quantity of reserves affects the real interest rate, this only changes inflation if the central bank does not change the interest rate on reserves. If monetary policy takes this effect of QE into account in its interest-rate policy, it can undo any effect of QE on inflation. Ultimately, it is interest rates that control inflation, not QE per se. Consistent with the goal of this

paper of focusing on inflation, one can be agnostic about the effects of QE on real activity and financial stability, because they do not undermine the (in)effectiveness of the policy with respect to inflation.

There are some reasons to be skeptical of an effect of QE on real outcomes. In fact, assuming neutrality of QE with respect to the real interest rate is more consistent with saturation in the market for reserves. Beyond the saturation point v^s, reserves provide no liquidity services and behave just like any other financial asset. In particular, reserves become substitutable with government bonds. But then, when the central bank through QE issues reserves to buy government bonds, it is just exchanging two forms of government liabilities. Each of them is denominated in nominal terms, each promises a certain nominal return next period, and bar a fiscal crisis each delivers on this promise and leads to the same transfer of resources between the government as a whole and the private sector. The logic of the Modigliani-Miller theorem applied to the government then implies that this swap of one government liability for another should have no effect on any real choice.[13] Moreover, most of the reasons for why the Modigliani-Miller theorem may fail for private corporations do not apply to QE, since reserves and government bonds have the same tax treatment and the same governance structure of the overall government behind them.[14]

The academic literature has come up with four main sets of reasons why QE may have further effects on inflation through real activity, two of them financial and the other two fiscal. The first is when there is a financial crisis that raises the value of liquidity, thus shifting v^s to the right.[15] The second focuses on financial frictions that prevent arbitrage between reserves and government securities of different maturities, so that different government securities can then have their own clienteles.[16] By issuing reserves to buy government bonds of different maturities, the central bank can affect the interest rate spreads between those assets and potentially change the effective cost of capital in different sectors of the economy. Both of these financial arguments go back to making the economy no longer being saturated with

reserves. Of course, by issuing even more reserves, the central bank could go back to the saturation zone. Moreover, the evidence put forward so far, and in the rest of this section, suggest that since 2011 or so, the U.S. economy has been saturated with reserves.

The third argument for QE to have real effects is in case of a fiscal crisis. Government bonds now carry sovereign risk, which reserves do not, since they are the unit of account. By engaging in QE, the central bank affects the overall supply of safe assets in the economy.[17] However, empirically it is hard to see much evidence that QE has had an effect on the perceived default probability of the United States so far, or that there is any sovereign risk at all priced in by financial markets. The fourth and final argument is that, if fiscal authorities try to force the central bank to inflate away the debt by not planning to pay for past debts, then the maturity of overall outstanding government liabilities will affect the size of the surprise debt-driven inflation. QE, by issuing short-term reserves and buying long-term bonds, changes the maturity of the debt as long as the Treasury keeps unaltered the maturity profile of its debt issuances. Therefore, QE will affect how much surprise inflation there is in a fiscal crisis, which via nominal rigidities affects real activity. This channel requires that the Treasury both actively manages its public finances and passively manages the maturity of the debt.[18]

A large empirical literature in the last few years has established that asset purchases by the central bank during the financial crisis had an effect on financial conditions.[19] The related but different question of whether QE has an effect on real activity in an economy saturated with reserves remains unanswered.

III.B Data and empirical strategy

QE built up gradually over time and was adopted endogenously in response to macroeconomic conditions, so isolating its effect on inflation (or anything else) poses a difficult identification problem. The literature has dealt with this by looking not at the implemen-

tation of the policy but at the partly unexpected announcements about QE and by relying on financial prices to reveal the expected effects of the policy rather than measuring their actual effects.[20] I pursue this event-study empirical strategy here as well.

QE policies in the United States have had four stages so far. The first, QE1, refers to the large-scale asset purchases (LSAPs) that started with the FOMCs November 25, 2008 announcement that it would purchase $100 billion in debt of the housing-related government-sponsored entities and up to $500 billion in agency mortgage backed securities. There was a second important announcement on March 18, 2009 of further purchases of $100 billion of agency debt and $750 billion of agency mortgage-backed securities, together with $300 billion of longer-term Treasury securities. Unfortunately, the data on inflation options that I will use (and describe soon) is of very poor quality around this time, since the market for these options was small and illiquid, so I can only use (noisy) data for the second date. QE2 refers to the second round of LSAP that started on November 3rd of 2010. The FOMC announced it would purchase a further $600 billion of longer-term Treasury securities. QE3 instead refers to the maturity extension program (MEP) announced on September 21 of 2011. Commonly referred to as "operation twist", the MEP consisted of purchasing $400 billion of Treasuries with maturities between 6 and 30 years, while selling the equivalent in securities maturing in 3 years or less. Finally, I consider a fourth event QE4, in the opposite direction. On May 22, 2013, Chairman Bernanke stated that "in the next few meetings, we could take a step down in our pace of purchase," which was interpreted as a sign that the Fed would taper its purchases of securities. Some tapering was later implemented in successive episodes in 2014. This QE4 episode was the closest to a negative shock to QE so far.

I also consider an extra 6 dates of intermediate announcements on the scale and pace of QE2, QE3, and QE4, giving a total of 10 event dates. The appendix describes these and why they were chosen. For each date, I look at the change in market expectations from financial contracts between the day before and the day after the announcement.

The data on financial prices about inflation comes from the market for over-the-counter inflation options. This market emerged in 2002 and has grown very quickly, so that by the end of 2009, there is a large volume of transactions and many price quotes giving reliable indicators of market expectations. This is after the main QE1 date. For the March 18 date, there are some data, but calculating reliable estimates of expected inflation requires combining data from up to 6 days before and after the announcement, and is only possible for a few maturities. For the other dates, there are market prices for future annual inflation from one year ahead to ten years ahead, and for cumulative average inflation from the present to 1 to 10 years ahead, as well as 12 and 15 years. Because inflation options give market bets on whether inflation will be above or below numbers between -3% and 6% in 0.5% increments, they can be used to non-parametrically estimate the market implied risk-adjusted probabilities of inflation. I complement these estimates with the implied volatility in the options, and (much easier) also expected inflation from the swap rate.[21]

III.C QE and the distribution of expected inflation

Figure 7 plots the change in risk-neutral expected inflation according to inflation-indexed swaps, at maturities 1 to 7 years, between the day before and the day after each of the 10 QE dates. The effects are typically small, with the largest following QE1, which caused a 0.36% increase in expected inflation one year out. There is a slight downward trend in time in the responses, but more often a bouncing up and down.

These results use only easily accessible data but they focus on a single moment in the distribution of inflation expectations. With all the information in inflation options, which provide estimates of the entire distribution, one can go much further. Figure 8 shows this distribution for the four major QE dates, for the 1-year ahead expected inflation, 5-years ahead, and finally for the average inflation over the next 10 years. For the QE1 date, there are no reliable data for the 10-years options or the 1-year; I show instead the 3-year

distribution. The results strikingly show how focusing on the mean can be misleading. The shift in expectations due to QE1 is now clearly visible, not because of its modest effect on average inflation, but rather by the decline in dispersion and in the probability of the tails. Moreover, the contrast with the other three QE dates is also apparent. QE2, QE3, and QE4 all had barely any noticeable effect on any moment of the distributions at all horizons. The exception is QE3 at the 1-year horizon, and there the distribution slightly shifted to the left, contrary to what might be expected.

Figures 9-11 illustrate this in terms of a few useful moments but now for all 10 QE dates. The first moment is the implied volatility in the options, one measure of the dispersion of inflation expectations. QE1 had a very large effect on this moment, but the other 9 QE dates saw little change in dispersion. Figure 10 shows that QE1 lowered the probability of deflation in the United States for 6 of the 7 horizons by about 15% in a short window of time. None of the other 9 QE programs that followed had an effect above 4% on the probability of deflation.[22] Figure 11 looks at the other side of the distribution, showing the change in the probability of inflation above 4%. QE1 again lowered this probability, so that it did not raise inflation expectations but rather compressed them.

A more systematic way to look for differences is to calculate statistics for the null hypothesis of no average change, as would be done in the typical regressions in event studies. Yet, this has two shortcomings. First, it pools together all QE dates, when some were arguably less anticipated than others, and each involved different changes on the asset side of the central bank's balance sheet. Second, it would focus only on one or a few moments, when we have data on the entire distribution at each data for many different maturities.

Instead, for every date, for every horizon available from 1 year to 15 years, for both year-on-year inflation and average cumulative inflation, I calculate the Kolmogorov-Smirnov statistic for a change in the distribution between the day before and the day after the QE announcement. Figure 12 plots all 186 statistics, recalling that each is computed using 19

percentiles of the distribution. To reject equality at the 5% significance level for a single test would take a statistic above 0.44. Especially from QE2 onwards, almost all the statistics are quite small, well below this threshold, reflecting what the particular moments already showed: announcements of quantitative easing had barely any effect on inflation expectations.

To conclude, the data on inflation expectations provides suggestive support for the hypothesis that once the market for reserves was saturated, further announcements on changes in the size of the liabilities of the central bank have little to no effect on inflation expectations.

IV Is sustained QE financially feasible?

Reserves at the end of 2015 stood at 13.4% of U.S. GDP. The evidence in the previous sections suggests that this amount has saturated the market for reserves, allowing the Fed to change its amount to pursue other goals than inflation, while at the same time being free to set the interest on reserves to aim at its inflation target. New QE policies that lower the amount of reserves would be subject to a lower bound in v^s, since if reserves fell below this amount, the market would stop being saturated. This section investigates the upper bound for reserves and future QE. Alternatively, it asks whether reserves can stay at their current high levels. Keeping with the focus on liabilities and inflation, the section describes the financial constraints of the central bank in terms of its ability to honor the promised payments on reserves, and whether the risk of funding QE may compromise the inflation target.

IV.A Central bank solvency

While the law has a clear definition for the solvency of a private institution or individual, economics has no clear consensus on how to treat it. In the benchmark model of consumer behavior, households always pay their debts, otherwise others would not lend to them.

Therefore, in the case of a central bank (or any other government agency) where no legal definition of insolvency applies, but at the same time there surely is some real constraint on resources that can be created or distributed, there is an understandable confusion on what insolvency means.

A recent literature has defined central bank insolvency as occurring when banks no longer want to hold reserves at the central bank.[23] This connects to the creation of the Federal Reserve, for it would imply that banks no longer want to use the Fed as the clearing house. It also has a direct link to economic theory because since reserves are liabilities of the central bank, private banks would not want to hold them if they were a Ponzi scheme. Therefore, requiring central bank solvency becomes equivalent to putting a no-Ponzi scheme condition on central bank reserves not being able to explode. Finally, this definition has empirical content. The other side of the coin from banks not wanting to hold reserves is for those reserves' value to be zero. But, since the real value of reserves is just the inverse of the price level, central bank insolvency is equivalent to hyperinflation, which happens often, all over the world.

This approach to central bank insolvency requires a second leg to stand on. If the fiscal authorities were always willing to transfer an unlimited amount of resources to the central bank, then central bank solvency would become subsumed by overall government solvency. The no-Ponzi scheme constraint on reserves would be replaced by the no-Ponzi scheme on overall government debt. Central bank insolvency is tightly connected to central bank independence, which puts limits on the fiscal support that the central bank can receive from the rest of the government. Being clear about the limits to the remittances (or dividends) between the central bank and the fiscal authority, and whether these are legal or political, then provides a clear measure of central bank solvency.[24]

Hall and Reis (2015) observe that for the major central banks, the strict rule in their mandates is to pay their annual net income to the fiscal authorities. They show that, if

this rule is followed, then the central bank will *always* be solvent, no matter the size of the balance sheet or the composition of the assets. QE can be sustained and expanded without the solvency constraint binding. However, a corollary of this result is that, depending on the risks that it takes, the central bank may have negative net income that calls for transfers from the fiscal authority. Especially if these are repeated, it is likely that the fiscal authority would refuse, putting the solvency of the central bank at risk. In that case, the income risk brought about by QE would put a limit on this monetary tool.

IV.B The income risk from QE

The net income of a central bank is equal to the seignorage from printing banknotes plus the return it earns on its assets minus the interest it pays on reserves. Keeping the focus on inflation, income risk matters in two ways. First, in the extreme case where the losses push the central bank to insolvency, hyperinflation follows. Second, a central bank that faces losses may be tempted to deviate upwards from its inflation target in order to increase its seignorage revenue.[25]

Issuing reserves per se does not cause income risk. If the central bank buys very short-term liquid government bonds with the extra reserves, it will earn the market interest rate on the assets, while paying the interest on reserves on its funding. The gap between the T-bill rate and the interest on reserves is approximately zero, and almost always positive. Therefore, the solvency constraint on the size of the central bank balance sheet is lax, and as long as the central bank can keep on buying safe short-term government bonds, it can keep on issuing reserves.

Yet, most central banks buy other assets than short-term government bonds. Foreign currency is one of the most prominent, and comes with income risk in the form of changes in the exchange rate for the currency. Likewise, in response to the financial crisis, many central banks bought privately-issued bonds, which come with the usual risk of default and

capital losses. If reserves are issued to buy these risky assets, then saturating the market for reserves would come with an increase in the risk that the central bank becomes insolvent.[26] However, these policies are best described as exchange-rate interventions or credit easing. QE refers instead to buying safe government bonds alone.[27]

Typical QE policies buy long-term government bonds. They come with a different source of income risk: interest-rate risk. For all four of the major central banks today, a sudden steepening of the yield curve would imply a capital loss in their large holdings of long-term government bonds.[28] Moreover, interest-rate risk causes a specific new type of danger for inflation beyond solvency. If the central bank fears making losses on its portfolio, this may keep its attention away from the inflation target. In particular, if the central bank fears the income risk of a steeper yield curve, it may delay raising interest rates for too long, which may let inflation take off.[29]

To reduce the maturity mismatch between assets and liabilities and the risk associated with it, the central bank would want to hold almost only short-term government bonds against its reserves. For the Federal Reserve, this would require a new round of QE in the form of a large-scale reverse operation twist. Otherwise, because this risk comes with a gain for the fiscal authority issuing the bonds, one way to deal with it would be to redistribute gains and losses back into fiscal hands. One alternative is to obtain further fiscal support from the government against this risk, as the Bank of England did by using its Asset Purchase Facility, which is indemnified by the government. Another alternative is to either provision against this risk, or run a deferred account: whenever the central bank makes a loss, it records it in this account, and deducts future positive net income from it before sending any dividends to the fiscal authorities.[30]

Aside from interest-rate risk, buying long-term bonds raises a different constraint to the expansion of QE. There must be enough longer-term bonds for the government to buy. At the end of 2012, the Federal Reserve already owned a little less than half of the U.S. government

debt of more than 5 years maturity.[31] A separate constraint facing the ECB is that the bonds of some governments have a significant amount of sovereign risk. By buying them using risk-free reserves, the ECB raises the supply of safe assets to a particular sector of the economy, the banking sector, which perhaps most needs it during a period of fiscal crisis and stagnation.[32] But the other side of QE is to bring sovereign risk into the balance sheet of the central bank, to which I turn next.

IV.C A solvency upper bound for QE

Through QE, the central bank becomes one of the largest individual holders of government debt, so a significant amount of public spending is devoted to paying interest to the central bank. In a fiscal crisis, sovereign interest rates rise and the payments to the central bank can become very large. It is tempting to force upon the central bank a write-off of the government debt as an alternative to further cuts in spending or increases in taxes. Given its uncomfortable role as being a part of the government, but independent from it, the central bank may find itself unable to prevent this loss.

Taking this fear to the extreme gives a useful bound on the feasible size of reserves. If all of the central bank's assets become valueless, then the central bank can only back its reserves with the present value of its seignorage revenue from issuing banknotes. As long as reserves are lower than the present value of seignorage, the central bank can back these liabilities with the future flows of seignorage, retiring them over time without running a Ponzi scheme. The present value of seignorage therefore gives a solvency upper bound for the central bank: in the worst case scenario where all of its assets return -100%, the central bank will be solvent as long as reserves are below this upper bound.

Estimating the present value of seignorage presents a few challenges each leading to uncertainty on the estimates. First, one needs to choose among different models for seignorage, and especially for how it changes with inflation. Second, one needs to estimate the param-

eters of each model. Third, one needs a valid stochastic discount factor to discount future seignorage revenues that depend on the level of inflation. And fourth, one needs a risk-free rate with which to discount the future. Hilscher et al. (2016) find that the two quantitatively largest sources of estimation uncertainty are the first and last: the model used, and the safe rate for discounting. Table 4 shows some of their estimates across different combinations for each.

Across columns are the models used to estimate the seignorage function. Partial-equilibrium models estimate the seignorage function directly, by relating seignorage to inflation alone. General-equilibrium models add the Phillips consideration that inflation may affect real variables which then feed into seignorage, and so estimate the seignorage function as one relation within a macroeconomic system. Reduced-form estimates use unrestricted regressions, while structural ones use economic models to pin down how seignorage varies with inflation.

Across rows are the risk-free rates used. The first row uses 2% to discount the future. This is a conventional choice using historical U.S. data to match the difference between the after-tax return to capital of about 4% and the growth rate real GDP per capita of about 2% per year. The field of climate change has seen some of the most heated debates on what value should be used to discount the future. The second row uses the Stern review's choice of 1.4%. Finally, the last row uses a discount rate based on market real rates in forwards markets, leading to a discount rate of 1.08%. Unsurprisingly, the lower the discount rate is, the higher the present value of distant seignorage, so the higher the solvency upper bound.

The different estimates of the present value of seignorage are all above 10-11% of GDP, the value of outstanding reserves in 2011-12, after which our previous estimates confidently suggested that the market for reserves was saturated. Even considering the worst case scenario in the solvency upper bound calculations, QE has not put the central bank solvency at risk. The elevated balance sheet of the Federal Reserve appears to be sustainable. Further rounds of QE may face up against the solvency constraint, but judging by this extremely

conservative measure, that risk is still far away for the United States.[33]

V The composition of QE

So far, this paper argued that the U.S. market for reserves since 2011 has been saturated, so changes in the size of the Fed's balance sheet have little effect on inflation, but changes in nominal interest rates do. Following a policy rule to set nominal interest rates today and to provide forward guidance for the future allows the central bank to pursue its inflation target. Yet, when nominal interest rates are close to zero, one might worry the central bank is out of policy tools. This section argues that this is not the case. With a saturated market for reserves, if the central bank finds itself very far from its target, it can innovate on the composition of the central bank liabilities. This section considers three such innovations for desperate times: the first is to issue banknotes instead of reserves, the second is to change the way reserves are remunerated, and the third is to change their maturity.

Right away note that while all three are somewhat radical, they have been used before either in smaller scales or with other goals. Centuries ago, central banks in Europe almost entirely issued banknotes in their operations, although their focus was on balancing the collection of seignorage against the control of inflation and they were frequently on the verge of insolvency or past it. Many central banks have also in the past accepted deposits of different maturities, including from the public, but these were used to make loans on the asset side as the central bank performed banking operations allocating credit to some sectors in the economy. The proposals studied here stay within the strict realm of monetary policy and the focus on inflation. Moreover, note that households and firms might react to these changes by being reluctant to hold the banknotes or the new reserves, but this does not imply the policies were a failure at raising inflation. After all, if economic agents are less willing to hold these units of account, that means their value goes down, which just means

the price level will go up.

V.A Currency instead of reserves

In the simplest version, this proposal consists of the central bank printing banknotes and giving them out for free to private agents. Milton Friedman famously illustrated this with a helicopter flown by the central bank dropping banknotes over a crowd. A more practical alternative would consist of the government issuing government bonds to pay for checks sent to households, just like it does with other social transfers, and perhaps subject to similar attempts at targeting. The central bank would then print banknotes to buy these government bonds and immediately write them off from its balance sheet leading to the same end result, but now using the fiscal authority as the distributor. This version is sometimes called overt monetary financing of the deficit.

Just like the discussion of QE in this paper, this proposal also expands the central bank's balance sheet, it also focuses on the liabilities, and it also has a main goal of raising inflation. At the same time, it is quite different because a different liability is used and the assets bought are worthless. More importantly, this policy's effect on inflation works through three channels that are distinct from those discussed in this paper so far. In fact, helicopter money is the antithesis of QE.

The argument for helicopter money starts by assuming that the central bank can perfectly control the supply of banknotes and so permanently raise it forever. With more money chasing the same goods, the argument goes, prices must rise.[34] Yet, recall again that in the current monetary system, the central bank does *not* exogenously choose how many banknotes to print. If banks choose to bring their banknotes to the central bank and deposit them as reserves, it must honor this request. Because banknotes earn zero interest, households would be expected to deposit these banknotes in banks to earn a positive deposit rate, who in turn would deposit them as reserves at the central bank to earn the positive interest on reserves.

There is little evidence that households are constrained from carrying the desired amount of banknotes in their pockets, so this substitution towards reserves would likely be large. The central bank might print many banknotes to end up with the same currency in circulation and just an increase in reserves, just like in standard QE.[35]

The only way to solve this control problem would be to stop paying interest on reserves, which would lead to a dramatic contraction in the size of the balance sheet of the central bank as excess reserves would go to zero very quickly: it would be the end of QE. To prevent it, the central bank would have to dramatically raise the required reserves that banks must hold at the central bank. In terms of figure 3, this would shift v^r to the right of v^s and the demand curve would now have an L-shape, vertical at the required level of reserves, v^r and horizontal to the right of this point. Yet, this would amount to a significant financial repression, as banks would be forced to hold around 10% of GDP at the central bank for no interest; when nominal market interest rates are back to their usual level of 4%, this would amount to a $74 billion annual tax on the financial sector.

Second, the increase in the supply of banknotes must meet a stable demand for real balances to generate the permanent increase in the price level. Decades of experience with monetarism and measuring the demand for banknotes has found that there are large and frequent shocks to the desire to hold banknotes, both in the short and in the long run. Calibrating the necessary increase in banknotes to obtain a desired increase in the price level is a daunting task. More fundamentally, the Lucas critique would be sure to hit in full force. With central bankers announcing they would be sending checks to each citizen, journalists describing how the printing press was running out of ink working overnight, and economists commenting that this was a permanent new state of the world, it seems likely that trust in the monetary system would be questioned leading to unpredictable shifts in the demand for currency. In contrast, QE relied only on staying in the horizontal segment of the demand curve for reserves.

Finally, the third part of the argument for why monetary financing of the deficit works comes from the fiscal stimulus it provides, which tends to raise economic activity, and in doing so stimulate inflation. The size of the transfer to households is equal to the seignorage revenue that the central bank no longer collects, and it is also matched by smaller transfers from the central bank to the fiscal authority every year from then onwards. QE instead is a fiscally neutral policy: because government liabilities are created to buy other government liabilities, the overall fiscal stance is unaltered.[36]

V.B Real payment on reserves

The central bank is the monopoly issuer of reserves, which are the unit of account. In the same way that in an economy saturated with reserves, the central bank can choose whichever nominal interest rate it wishes to pay on those reserves, it could alternatively choose to remunerate reserves differently. Hall and Reis (2016), building on earlier work by Hall (1997), proposed in 2012 an alternative way of remunerating reserves that would give the central bank better control over the price level.

Instead of promising an interest rate, the central bank could offer reserves that promised an indexed payment. For each \$1 of reserves, the bank could receive a payment tomorrow that was indexed to the price level then. If the promise was of x and the price level p today and p' tomorrow, the payment would be $(1+x)p'$. Abstracting away from uncertainty, the real return on reserves would be $(1+x)p'(p/p')$. Arbitrage ensures that this would be equal to the safe real interest rate in private investments in the economy r. Therefore, the price level would be $p = (1+r)/(1+x)$.

For a given estimate of the safe real rate, if the price level was running below target, the central bank could lower the payment on reserves, and in doing so raise prices. The intuition for how this works is the following. When the central bank promises a smaller payment, reserves are a less attractive investment, so banks will not want to hold them, and their

real value must fall. But since their real value is the inverse of the price level, prices must rise. As banks adjust their portfolios, the movement in savings and investment caused by a change in the promised payments will give firms the incentive to change their prices until equilibrium is restored. By promising a payment on reserves, the central bank gains a new tool with which to control the price level. Hall and Reis (2016) discuss many implementation details with this proposal and more thought and research would have to be put into it before applying it.

V.C Forward reserves

Currently, reserves are overnight deposits. During the crisis, central banks innovated with the time dimension of their liquidity programs. More prominently, the ECB complemented its one-week main refinancing operations (MRO) with longer-term repurchase agreements (LTRO) with maturities that ranged from 3 months to 3 years. There is no significant barrier to innovating as well with the maturity of deposits at the central bank. Banks could be offered the option to deposit funds at the central bank not just overnight, but also for longer durations.

If the effective overnight interest rate on these different reserve instruments were all the same, this would make little to no difference. The interest rates that applied to the ECB's LTRO program were variable and indexed to the MRO rate. In this case, the central bank continues to have a single policy instrument, the overnight return on reserves, and offering longer-duration reserves would not change the ability to control the price level.

If the central bank instead offered a fixed interest rate on these programs, the situation changes. In the same way that paying an overnight rate on reserves allows the central bank to affect overnight rates, forward reserves of longer maturities would give the central bank some ability to affect forward nominal interest rates associated with different maturities. Offering a menu of forward reserves of different maturities up to a certain horizon for banks

to hold, the central bank could exert direct influence on the nominal yield curve until that horizon. With a real yield curve determined in the equilibrium of the economy, this would give the central bank an additional tool to control expected inflation at different horizons in financial markets.

VI Conclusion

In the 1970s, research on central banking focused on real activity and the use of price controls and credit restrictions, yet the central banks of advanced economies found themselves unable to keep either inflation or unemployment from rising. A backlash against Keynesianism emerged and monetarism arose emphasizing inflation over real stability in the mandate of the central bank, and researching the theoretical properties of money, the empirical features of the demand for currency, the measurement of monetary aggregate multiples, and policies that targeted non-borrowed reserves.

In 2016, the concern is instead low inflation. The deviation from the mandate is today very far from being as severe as four decades ago, but the last two years and expected next two suggest a sizable downward risk to the price level. Moreover, recent and current research has partly neglected this risk emphasizing instead real and financial stability and on how targeted asset purchases can promote it. This paper argued for refocusing on the inflation mandate and on the liabilities-side of the central bank balance sheet. Where monetarism proposed a money-growth rule as a preferred policy and studied the demand for money, shocks to money supply, and the composition of monetary aggregates, this paper studies the policy of quantitative easing and tried to push forward research on the demand for bank reserves, the surprise component of QE announcements, and the composition of the funding side of QE.

The analysis concluded that QE shifted the market for reserves to a region where the

demand for reserves is horizontal and the supply vertical. Further expansions of the size of reserves are likely to have little effect on inflation, similar to the last rounds of QE, but by keeping the market saturated with reserves, they allow the central bank to use the interest rate on reserves to steer inflation. The current level of reserves is below the solvency upper bound for the Federal Reserve, and a large-scale reverse operation twist that re-populated the asset side of the balance sheet with short-term government bonds would almost eliminate any income risk. Overall, there are benefits to keeping the market for reserves saturated in order to be able to direct interest-rate policy directly to the control of inflation, while leaving QE for other goals.

Looking forward, keeping the market for reserves saturated is consistent with returning to a lean central-bank balance sheet. This means not zero excess reserves but rather closer to 1 trillion, or the size of the balance sheet in 2011, not pre 2008. The Federal Reserve can return to focussing on setting interest rates in order to control inflation, but now with its main target being the interest on reserves instead of the federal funds rate (and with a constant spread with respect to the interest on overnight reverse repos and the interest on the discount window). If more radical measures are needed to keep inflation near its target, I suggested innovating in the types of reserves issued while keeping the focus on the interest paid on them.

Throughout the discussion, there were many references to how fiscal authorities would respond. It is a general lesson of macroeconomics that the interaction of fiscal and monetary policy determines inflation (and other aggregate variables) so that the precise rules by which central banks are independent from fiscal authorities in some regards, but cooperate with them in others, are central to keeping inflation on target.[37] With a larger central bank balance sheet, the fiscal implications of monetary policy become more pronounced, so these rules become more important. How the market for reserves gets taxed, how financial regulation undertaken outside of the central bank treats bank reserves, how the central bank manages

its income risk, how dividends from the central bank are set, how government bonds held by the central bank are treated during a fiscal crisis, or how transfers of seignorage to the public would be offset by other fiscal transfers, are some of the many questions that arose and that were discussed. At one extreme, the central bank could change the assets in its balance sheet to consist of almost only short-term government bonds, and choose interest rates on reserves, and in doing so minimize the reliance on interactions with the fiscal authority. At the other extreme, it could do helicopter drops of banknotes, which are a clear fiscal policy in substitution of the fiscal authority. Where to be in between these two extremes will surely take central stage in debates on monetary policy in the next few years.

Appendix

A Harmonizing central bank balance sheets

Central banks are peculiar institutions. Their balance sheets are varied in their categories, they have some original methods to account for some activities, and they employ some concepts that are alien to someone trained in financial reporting for private institutions, from the Federal Reserve's reasoning for not booking government bonds to market, to the ECB's revaluation accounts that asymmetrically record capital gains on some assets, and including Bank of England's three separate balance sheets for the issuing department, the banking department and the asset purchase facility. Figure 1 puts forward my effort to rearrange the published accounts in a comparable way across the four institutions using a few key categories, and hopes to inspire others to expand and refine this harmonization work.

All the data is annual, covering the period from 2005-15, with the exception of the BoJ, for which there is no GDP data for 2015, and the Bank of England, because of a change in accounting procedures in 2007.

Federal Reserve: The source of the data is the annual reports of the Federal Reserve System, tables 2 and 9a. (1) Gold and foreign assets are gold and SDRs; (2) other assets include all else, especially the rescue operations in 2008; (3) short-term gov. bonds are holdings of Treasury bills; (4) long-term gov. bonds are holdings of Treasury bonds, agency debt and MBS; (5) capital is the sum of paid-in capital and surplus; (6) currency are banknotes; (7) others include repos and other liabilities; (8) bank reserves are deposits at Federal Reserve Banks.

European Central Bank: The source of the data is the annual report for the consolidated Eurosystem balance sheet. (1) Gold and foreign assets are gold and lending in foreign currency; (2) other assets include other assets and lending to non-euro area residents; (3)

MRO is lending to euro area credit institutions as part of main refinancing operations; (4a) LTRO is lending to euro area credit institutions as part of long-term refinancing operations; (4b) Securities sums securities held plus government debt of Euroarea residents; (5a) capital is capital plus reserves; (5b) is the revaluation account from marking some assets to market; (6) currency is banknotes (7) others include assorted liabilities not related to monetary operations; (8) bank reserves are liabilities to euro area credit institutions.

Bank of England: The source of the data is the Bank of England historical balance sheet and the annual reports for the Annual Purchase Facility. (1) Gold and foreign assets are always zero; (2) other assets include advances to the government, central bank bonds, and other securities; (3) Short-term repos are short-term repurchase agreements; (4) long-term gov. bonds comes from apportioning the APFs holdings of gilts to the Bank of England by the ratio of the APF liabilities to the Bank of England as a ratio of total assets; (5) capital is always zero; (6) currency is banknotes (7) others include FC public securities, cash ratio deposits, and others; (8) bank reserves are reserve balances.

Bank of Japan: The source of the data is the Bank of Japan annual review. (1) Gold and foreign assets are gold plus foreign currency assets; (2) other assets include cash, receivables, pecuniary trusts, fixed assets and others; (3) Short-term gov. bonds; (4) Long-term gov. bonds; (5) capital sum capital paid in, reserves and net income; (6) currency is banknotes (7) others include deposits of the government, payables under repos and provisions for losses; (8) bank reserves are deposits at the central bank excluding the government.

B Mathematical details behind figure 3

A bank optimally choosing its level of real reserves v_t at date t, takes into account their promised return $(1+i_t^v)$ as well as the liquidity benefits they give in terms of a marginal profit function $B(v) : [v_t^r, \infty] \to \mathbf{R}_0^+$ that has a non-positive derivative capturing the diminishing

marginal benefits of liquidity and a satiation point v_t^s such that $B(v) = 0$ for $v \geq v_t^s$. The optimality condition of the bank is:

$$\mathbb{E}_t \left[m_{t,t+1} \left(\frac{p_t}{p_{t+1}} \right) (1 + i_t^v) \right] + B(v_t) = 1, \tag{A1}$$

where $m_{t,t+1}$ is the stochastic discount factor used by the bank on its investment between t and $t+1$, and p_t is the price level. At the same time, the bank could invest in other financial assets, with potentially risky return i_{t+1}, and for those the optimality condition is:

$$\mathbb{E}_t \left[m_{t,t+1} \left(\frac{p_t}{p_{t+1}} \right) (1 + i_{t+1}) \right] = 1. \tag{A2}$$

Combining the two equations gives the demand curve plotted in figure 3:

$$B(v_t) = \mathbb{E}_t \left[m_{t,t+1} \left(\frac{p_t}{p_{t+1}} \right) (i_{t+1} - i_t^v) \right] \tag{A3}$$

where the price of reserves on the right-hand side is the expected ($\mathbb{E}_t$) risk adjusted ($m_{t,t+1}$) real (p_t/p_{t+1}) return on alternative assets (i_{t+1}) minus that on reserves (i_t^v) as stated in the text.

Beyond the saturation point, the optimality condition for reserves becomes:

$$(1 + i_t^v) \left[\mathbb{E}_t(m_{t,t+1}) \, \mathbb{E}_t \left(\frac{p_t}{p_{t+1}} \right) + \mathrm{Cov}_t \left(m_{t,t+1}, \frac{p_t}{p_{t+1}} \right) \right] = 1. \tag{A4}$$

Recall that $1+r_t = 1/\,\mathbb{E}_t(m_{t,t+1})$ is the safe real interest rate, and approximate this expression by ignoring the covariance term as in a linear approximation. Then, after taking logs and using the usual approximation that $\log(1 + x) \approx x$ and the definition of inflation $\pi_{t+1} = \Delta \log(p_{t+1})$, we get:

$$i_t^v = r_t + \mathbb{E}_t(\pi_{t+1}) \tag{A5}$$

For a fixed r_t a higher i_t^v raises expected inflation, the Fisher effect. But, since in a standard macroeconomic model $m_{t,t+1}$ is the ratio of marginal utilities over time, then r_t is approximately proportional to the expected growth rate of consumption (the Ramsey-Euler result) and in turn the Phillips curve relates the current level of consumption positively to inflation. Combining these gives a a negative relation $r(\pi_{t+1})$, and so a negative relation between the nominal interest rate and inflation in the short run, keeping inflation expectations fixed.

C Bank-level data on reserves

The primary data in the analysis comes from the call reports available for over 6,000 banks from the FFIEC website (https://cdr.ffiec.gov/public/PWS/DownloadBulkData.aspx). The years in analysis are 2005, 2007, 2011 and 2015 and in all cases only data from the 4th quarter are used. The variable names and codes available from the FFIEC data are: (i) Total assets (RCON217); (ii) Total deposits (RCON2200); (iii) Reserves with FED (RCON0090); (iv)US treasuries, both held and available for sale (RCON0213 summed to RCON1287). The definitions of all variables are available from the FED Micro Data Reference Manual (https://www.federalreserve.gov/apps/mdrm/). The dataset consists of a repeated cross section of banks which reports data on reserves for 2388 banks in 2015, 2179 in 2011, 2098 in 2007 and 2154 in 2005.

D QE dates

The main QE dates are:

QE1: March 18, 2009. The FOMC statement announced that the Federal Reserve would purchase up to an additional $100 billion of agency debt and $750 billion of agency mortgage-backed securities, bringing the total size of the respective purchase programs to $200 billion

and $1.25 trillion. The statement also introduced the decision to purchase up to $300 billion of longer-term Treasury securities over the next six months.

QE2: November 3, 2010. The FOMC formally announced that it would purchase a further $600 billion of longer-term Treasury securities by the end of the second quarter of 2011, a pace of about $75 billion a month. This announcement was widely anticipated, and it is possible that markets may have expected a larger QE program. For example, Goldman Sachs expectation was for about $750 billion in QE2. In addition, related announcements on November 4 - jobless claims and productivity - complicate interpreting changes around this date as solely the result of the FOMC announcement.

QE3: September 21, 2011. The FOMC announced that it would extend the average maturity of its holdings of securities (Operation Twist). It was stated that "the Committee intends to purchase, by the end of June 2012, $400 billion of Treasury securities with remaining maturities of 6 years to 30 years and to sell an equal amount of Treasury securities with remaining maturities of 3 years or less. This program should put downward pressure on longer-term interest rates and help make broader financial conditions more accommodative." In addition, it was announced that principal payments from agency debt and agency MBS would be reinvested in agency MBS, to help support conditions in mortgage markets.

QE-Taper: May 22, 2013. Chairman Bernanke gave testimony before the Joint Economic Committee. The prepared remarks reiterated existing Fed policy. In response to subsequent questions, Chairman Bernanke stated that "in the next few meetings, we could take a step down in our pace of purchase." This was interpreted by some market participants that the Fed would begin to taper its purchases of securities, despite the balanced tone of the prepared remarks.

On top of these, following Krishnamurthy and Vissing-Jorgensen (2011) and Gagnon et al. (2011), I used a few more dates of announcements:

QE2: August 10, 2010. The FOMC announced that Fed holdings of securities would be held constant at their current level by reinvesting principal payments from agency debt and agency MBS in longer-term Treasury securities, while maturing Treasury securities would continue to be rolled over at auction. The market expectation prior to this announcement was that the Fed MBS portfolio would gradually decline in size. Also novel was the shift towards longer-term Treasuries, rather than reinvestment in agency debt or agency MBS.

QE2: September 21, 2010 The FOMC statement maintained the existing policy of reinvesting principal payments from its security holdings, and also stated that the Committee was "prepared to provide additional accommodation if needed to support the economic recovery," which represented a shift in language from the previous statement, in which the Committee stated that it "will employ its policy tools as necessary to promote economic recovery and price stability." Many market participants interpreted this shift in language as a signal that the Fed would provide additional stimulus, and purchases of long-term Treasuries in particular.

QE3: August 31, 2012. Chairman Bernanke gave a speech at Jackson Hole that was interpreted by some market participants as signaling that there was room for additional policy accommodation.

QE3: September 13, 2012 The FOMC announced that it would increase policy accommodation by purchasing additional agency MBS at a pace of $40 billion per month. This together with the existing maturity extension and principal reinvestment programs were anticipated to increase holdings of longer-term securities by around $85 billion each month, through the end of 2012.

QE3: December 12, 2012 The FOMC announced that after its program to extend the average maturity of its holdings of Treasury securities was completed at the end of the year, it would purchase longer-term Treasury securities, initially at a pace of $45 billion per month.

In January it also planned to resume rolling over maturing Treasury securities at auction.

QE-Taper: June 19, 2013 Chairman Bernanke gave a press conference in which there was further discussion of tapering. He stated that "the committee currently anticipates that it will be appropriate to moderate the monthly pace of purchases later this year", and that under a baseline "moderately optimist" forecast, "we would expect probably to slow or moderate purchases some time later this year, and then through the middle of-through the early part of next year, and ending, in that scenario, somewhere in the middle of the year."

Notes

[1]Among many others, see Adrian and Shin (2010) or Gertler and Karadi (2013).

[2]See also Woodford (2016) for the interaction of QE and inflation with the zero lower bound.

[3]There is an active discussion on whether to interpret the legal mandate of the central bank as a price-level as opposed to an inflation target, and on what would be optimal (Reis, 2013a).

[4]In this conference, Goodfriend (2016) proposes breaking the one-to-one exchange rate between cash and reserves, while keeping reserves as the unit of account.

[5]The appendix formalizes this discussion. See also Friedman and Kuttner (2010).

[6]The central bank could choose to vary this requirement with the price of reserves, and the requirement is often expressed as a ratio to other endogenous variables, like the amount of deposits in the bank, which in general equilibrium may depend on the return on reserves. Therefore, the demand for required reserves need not be strictly vertical. This is immaterial for the discussion of QE, which involves voluntary excess reserves, moving the market always to the right of v^r.

[7]See Beltran et al. (2015).

[8]Friedman and Kuttner (2010) present evidence that before 2008, the market for reserves was close to the vertical range of demand.

[9]Ennis and Wolman (2015).

[10]Woodford (2003) is a classic reference and Reis (2015b) a recent survey.

[11]Duffie and Krishnamurthy (2016) in this conference argue for complementing movements in the interest on reserves with parallel movements in the interest rate on overnight reverse repurchase agreements.

[12]See also Cúrdia and Woodford (2011).

[13]Wallace (1981).

[14]Greenwood et al. (2016) in this conference discuss reasons why the maturity mismatch between reserves and even short-duration government bonds affects financial markets.

[15]Bernanke (2015).

[16]For instance, Vayanos and Vila (2009) or Greenwood et al. (2015b).

[17]Caballero et al. (2016) or Reis (2016b).

[18]Cochrane (2014), Reis (2016b) and Greenwood et al. (2015a).

[19]Joyce et al. (2012) is an already outdated summary.

[20]For instance Krishnamurthy and Vissing-Jorgensen (2011) and Gagnon et al. (2011).

[21]See Hilscher et al. (2014) for more explanations on the data.

[22]See also Kitsul and Wright (2013).

[23]Reis (2013b), Hall and Reis (2015), Del Negro and Sims (2015), Reis (2015a), Benigno and Nistico (2015), among others.

[24]See Sims (2003), Hall and Reis (2015), and Del Negro and Sims (2015). Reis (2015a) explores different lower bound constraints on the transfers from the fiscal authority to the central bank. Note that central bank net worth by itself is not a meaningful concept for a central bank in the same way it is not for the government as a whole, unlike what happens with private corporations.

[25]Del Negro and Sims (2015).

[26]Reis (2016a) discusses in detail the many sources of income risk that a central bank may face.

[27]The situation is more interesting in a currency union where some sovereign debt has a high risk of default. In that case, together with the income risk, there is a scope for using the central bank balance sheet to redistribute across regions (Reis, 2013b), which may be desirable or not.

[28]Bassetto and Messer (2013) and Hall and Reis (2015).

[29]Berriel and Bhattarai (2009) and Bhattarai et al. (2015).

[30]Hall and Reis (2015) and Benigno and Nistico (2015).

[31]Hilscher et al. (2014).

[32]Reis (2016b).

[33]One source of risk that these calculations ignore is that coming from private digital currencies that displace the use of banknotes, therefore capturing the seignorage revenues from the central bank. It is still too early to gauge how serious is this danger: for instance looking at two countries where financial technology is booming, Sweden and the United Kingdom, seignorage from banknotes has clearly fallen in the former in the last five years, but it has been elevated in the latter.

[34]See Krugman (1998) or Turner (2015).

[35]If the interest on reserves was brought to a significant negative value, then people may reach the point of indifference between banknotes and on reserves. But as soon as interest rates rise, the same argument would apply, and the currency in circulation would fall then. It is well known (Auerbach and Obstfeld, 2005; Cúrdia and Woodford, 2011) that printing banknotes during a zero lower bound only raises the price level if the supply of banknotes remains higher after the economy leaves the zero lower bound.

[36]Reis (2016a) discusses at length the changes in fiscal stance that result from central bank actions.

[37]See Leeper (2010) for an example in this conference series.

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Figure 1. Balance Sheets of Four Major Central Banks 2005-15

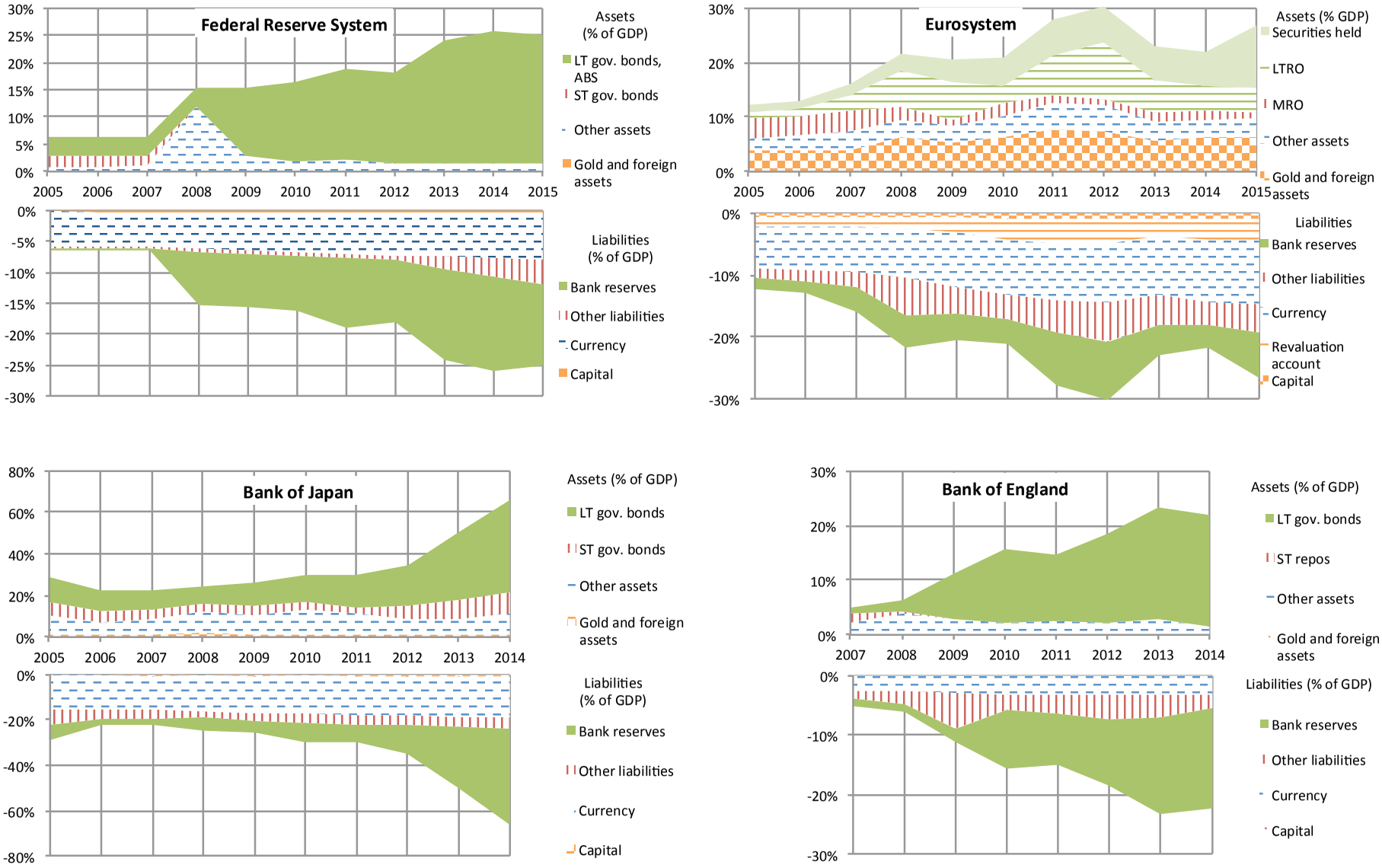
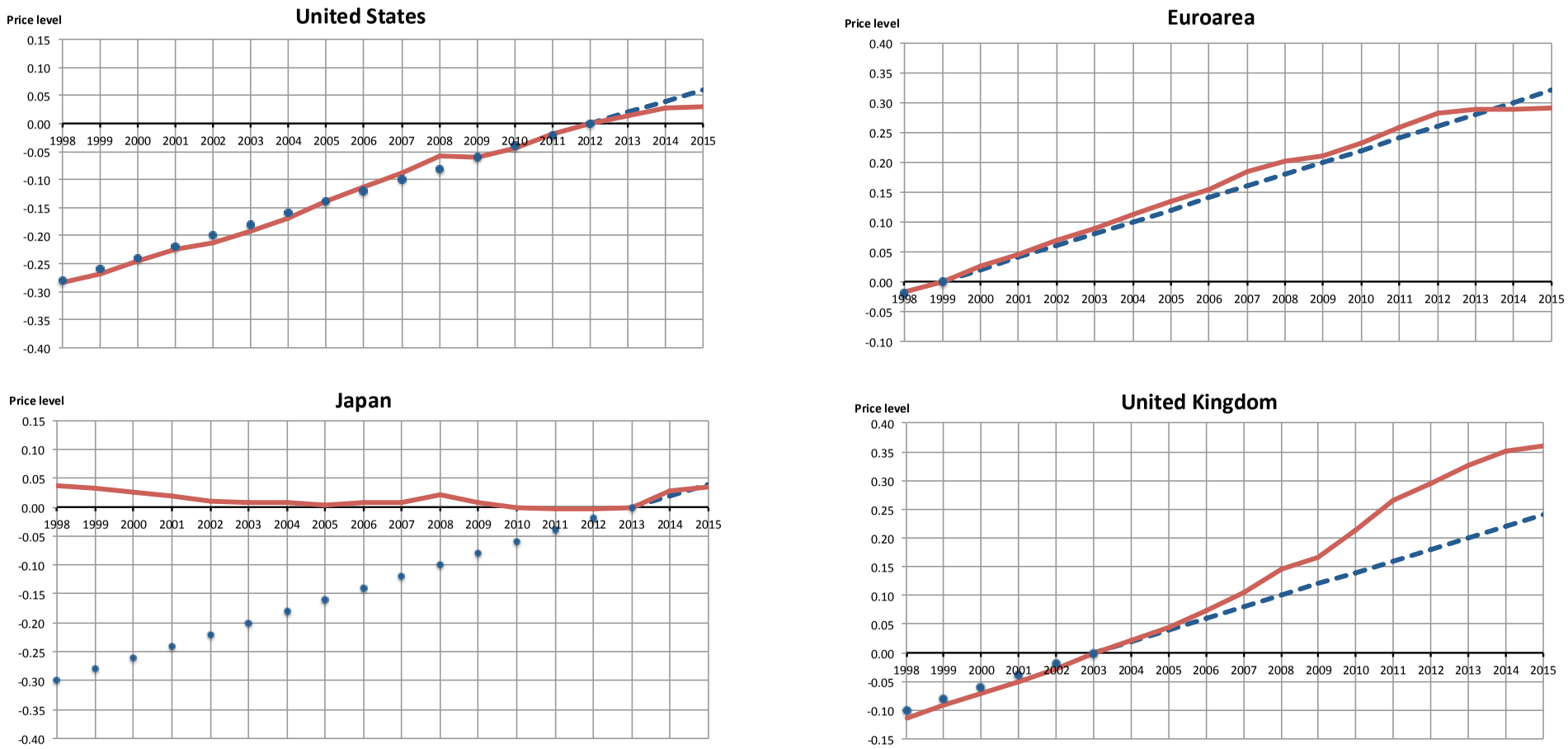


Figure 2. Target and Actual Price Level 1998-2015



Notes: The target price level is in the dashed blue line from the date of the announcment of the target forward, the hypothetical target is the extension of the target backwards in time, and the actual price level is in the solid red line. All are normalized to equal zero at the date of adoption of the target. For the United States, the inflation target was adopted in January of 2012 using the personal consumption expenditures deflator as the reference measure. For the Euroarea, the target was adopted in January of 1999 for the harmonized consumer price index. For Japan, the target for the consumer price index was adopted in January of 2013. For the Bank of England, the current target for the consumer price index target was adopted in December of 2003. The target for all four is a 2% annual growth in the price level. The vertial axis is in a log scale.

Figure 3. Equilibrium in the market for reserves

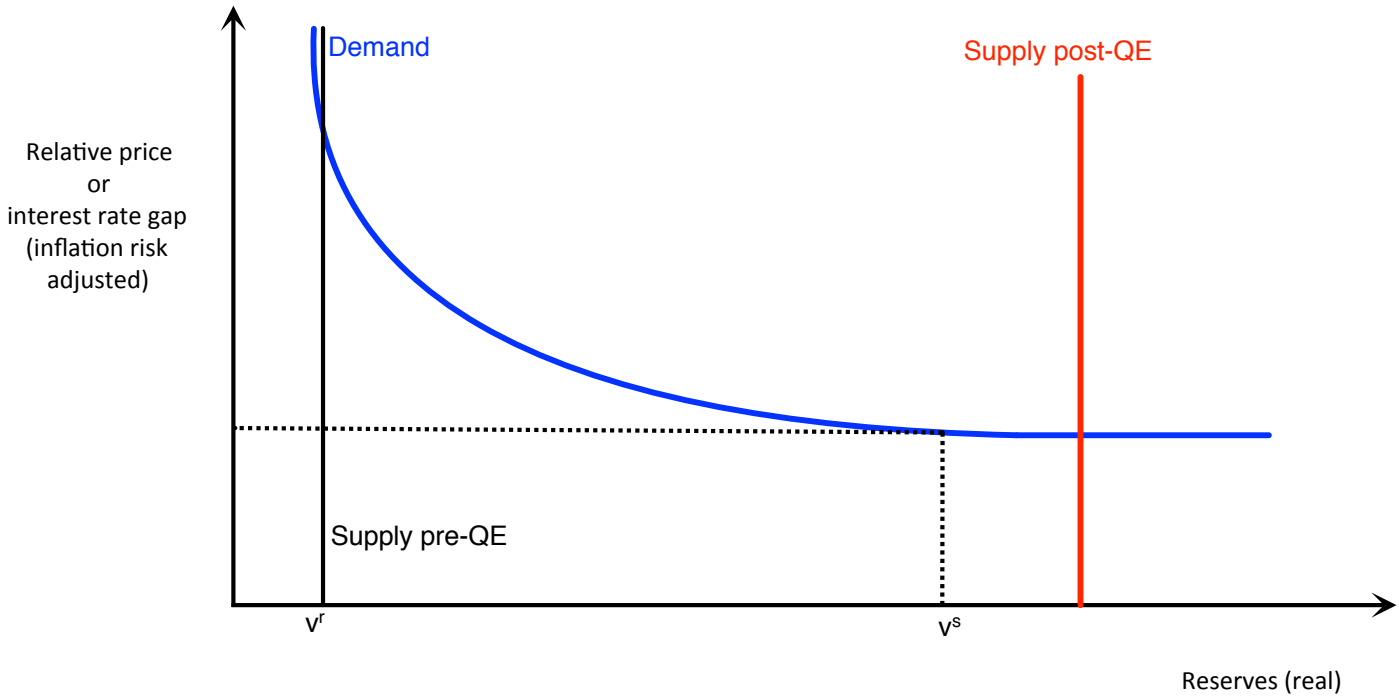


Figure 4. QE and the liabilities of the Federal Reserve

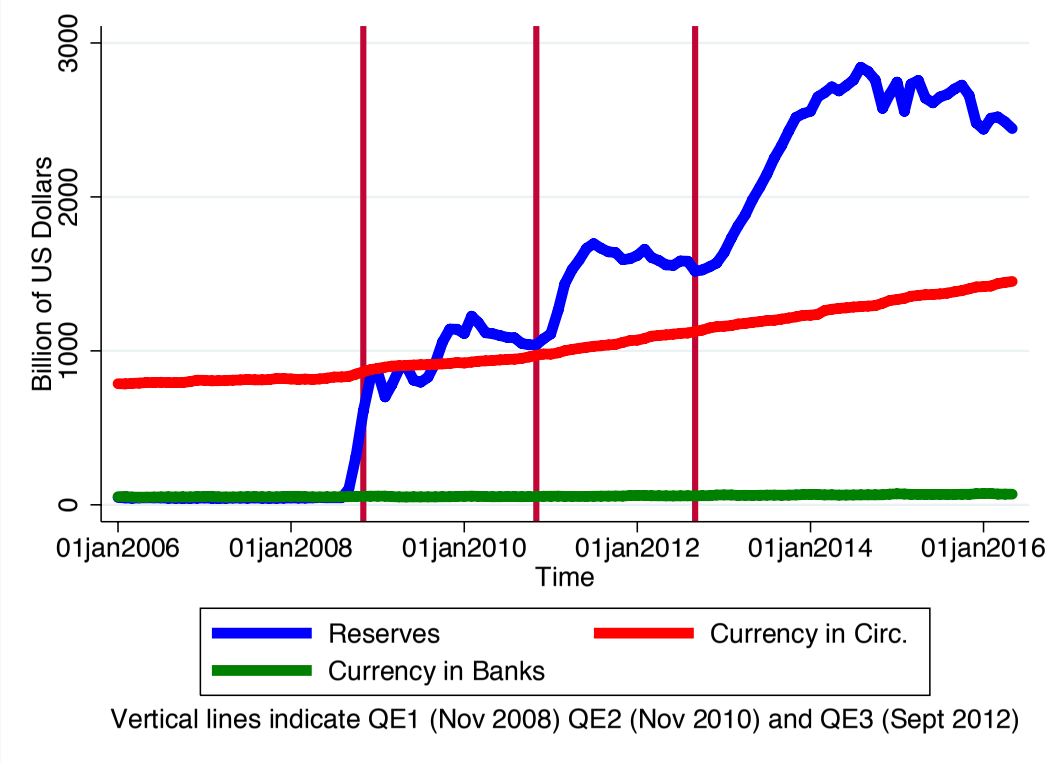


Table 1. The demand curve for reserves

Variables	(1) Reserves	(2) Reserves	(3) Reserves	(4) Reserves	(5) Reserves	(6) Reserves
$i_{\text{Reserves}} - i_{\text{FederalFunds}}$	-0.174		-0.119		-0.199	-0.467**
	(0.112)		(0.112)		(0.127)	(0.185)
$i_{\text{Reserves}} - i_{\text{Tbill}}$		0.0140		0.187	0.0878	0.352
		(0.156)		(0.162)	(0.171)	(0.219)
Obs	53	53	53	53	53	88
Trend	No	No	Yes	Yes	No	No
F Test	2.40	0.01	1.93	2.40	1.40	3.49**
Adj. R sq.	0.022	0.019	0.033	0.043	0.010	0.087

Notes: The left-hand side in all regressions is the difference in log real reserves. In columns 1 to 5, the sample goes from December 2011 to June 2016; in column 6 it starts in December 2008. A time trend is included in columns 3 to 6. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Figure 5. Distribution functions of reserves/deposits across banks

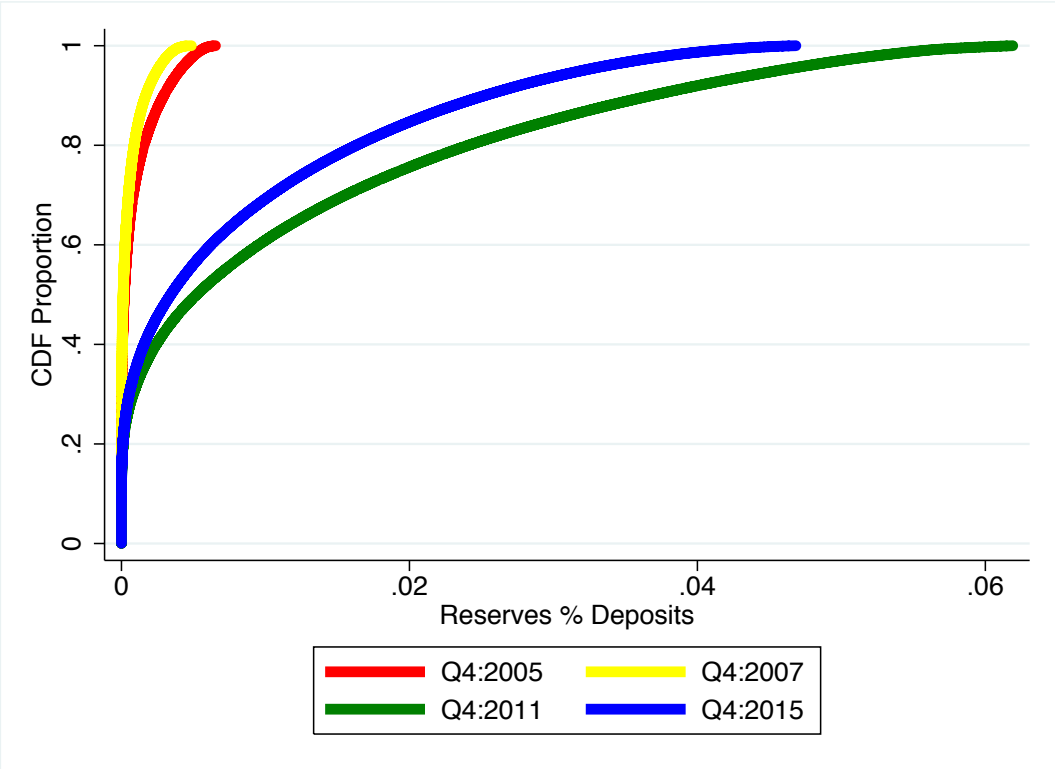


Table 2. Correlation matrix for reserves/deposits of same bank across time

	2005	2007	2011	2015
2005	1			
2007	0.477***	1		
2011	0.256***	0.870***	1	
2015	0.018	0.315***	0.018	1

Notes: *** p<0.01.

Figure 6. Distribution functions of reserves/assets across banks

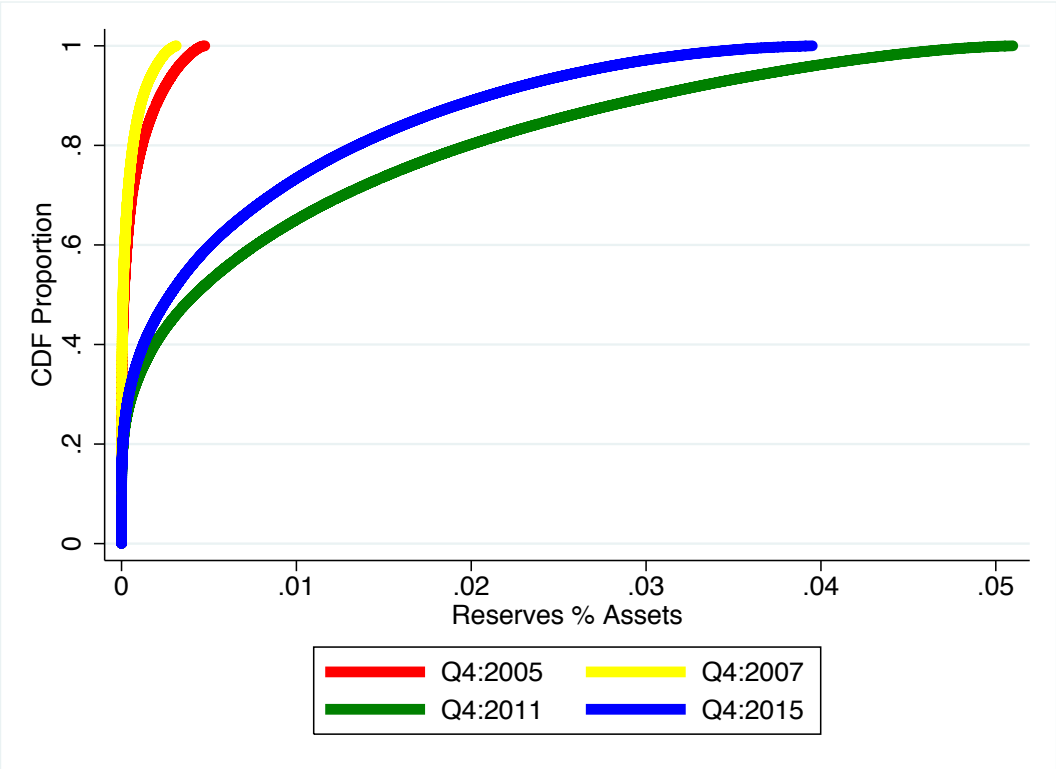


Table 3. Correlation matrix for reserves/assets of same bank across time

	2005	2007	2011	2015
2005	1			
2007	0.510***	1		
2011	0.152***	0.179***	1	
2015	0.139***	0.167***	0.619***	1

Notes: *** p<0.01.

Figure 7. Change in expected average inflation around QE dates

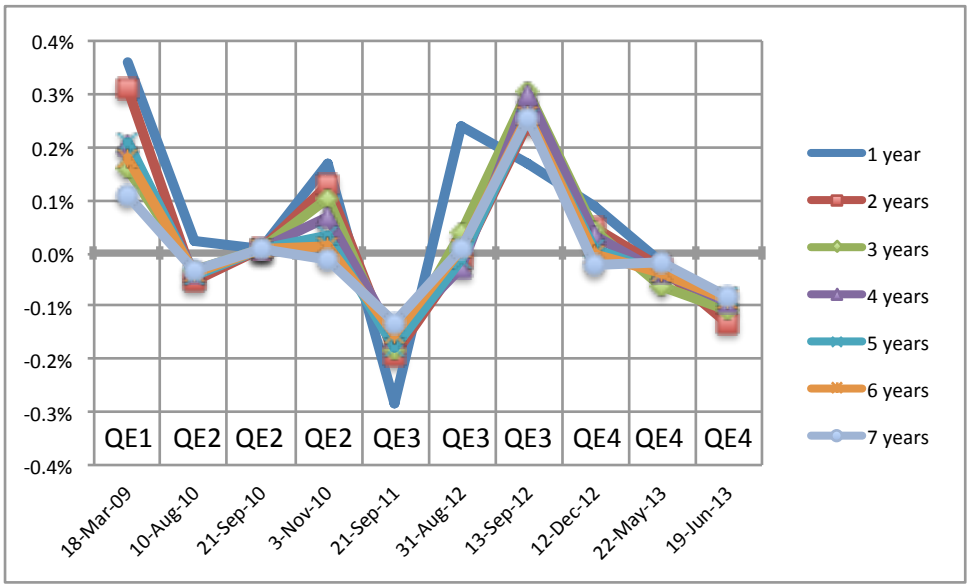


Figure 9. Change in expected volatility of inflation around QE dates

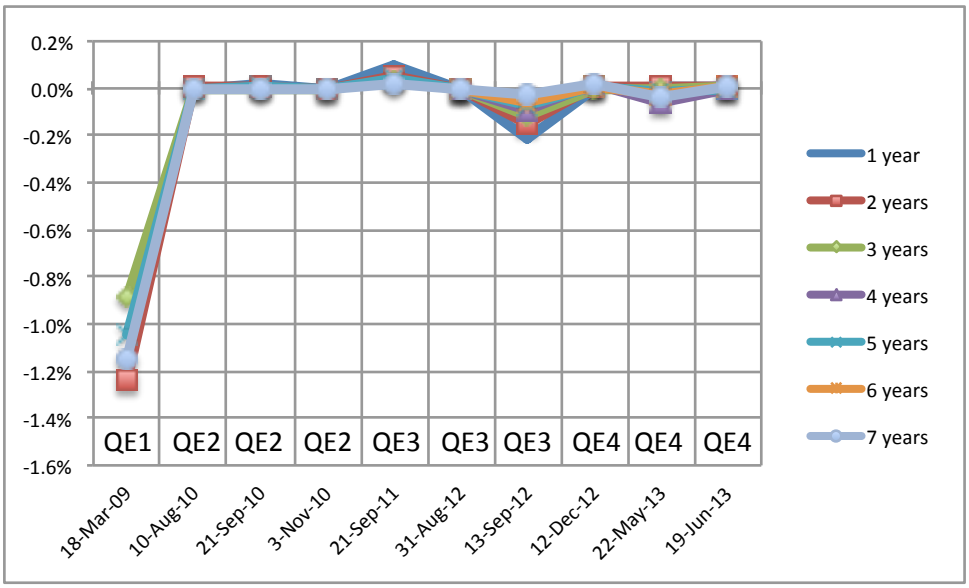


Figure 8. Options-implied density functions for inflation at different horizons around QE dates

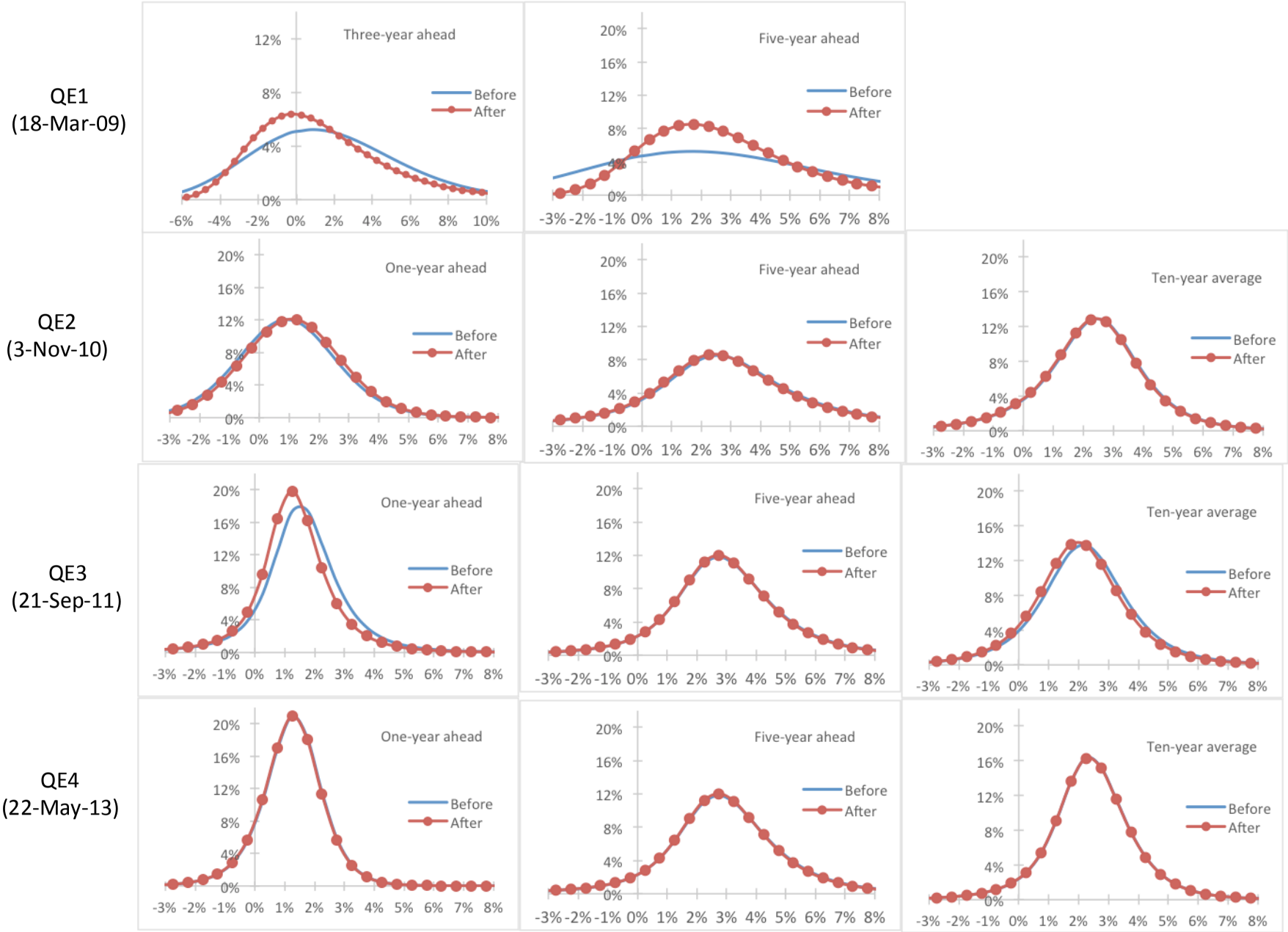


Figure 10. Change in expected probability of deflation around QE dates

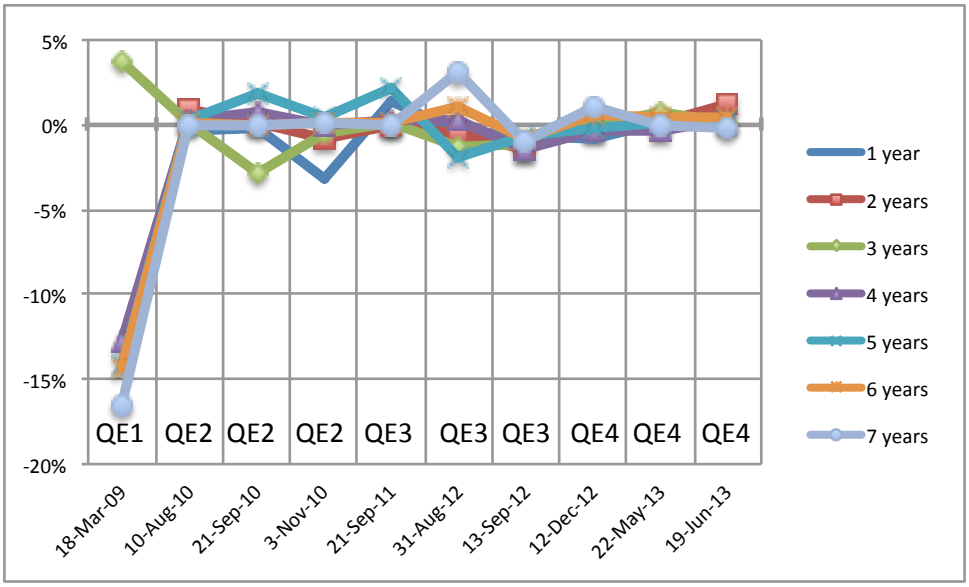


Figure 11. Change in expected probability of inflation above 4% around QE dates

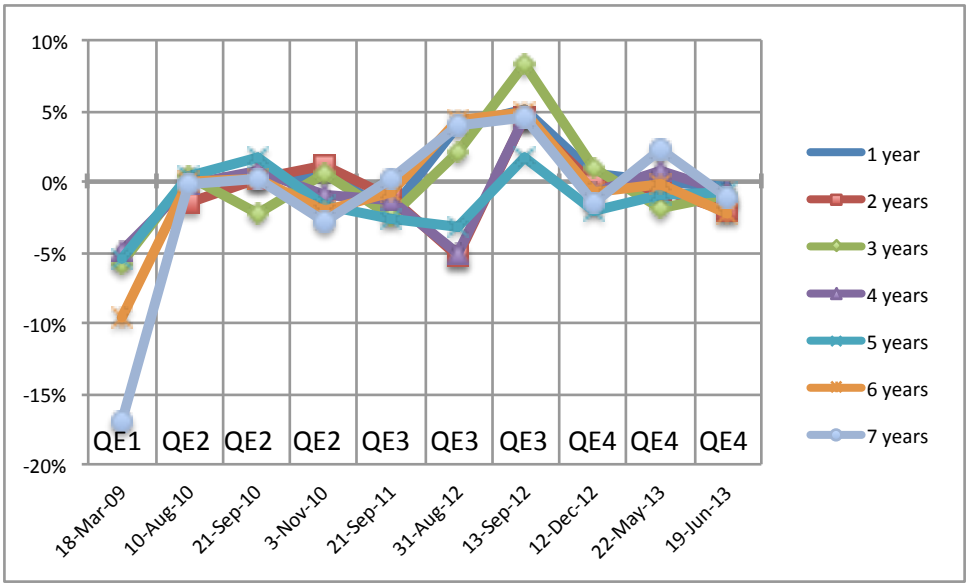


Figure 12. Kolmogorov-Smirnov statistics for a change in the distribution of inflation for all horizons at each QE date

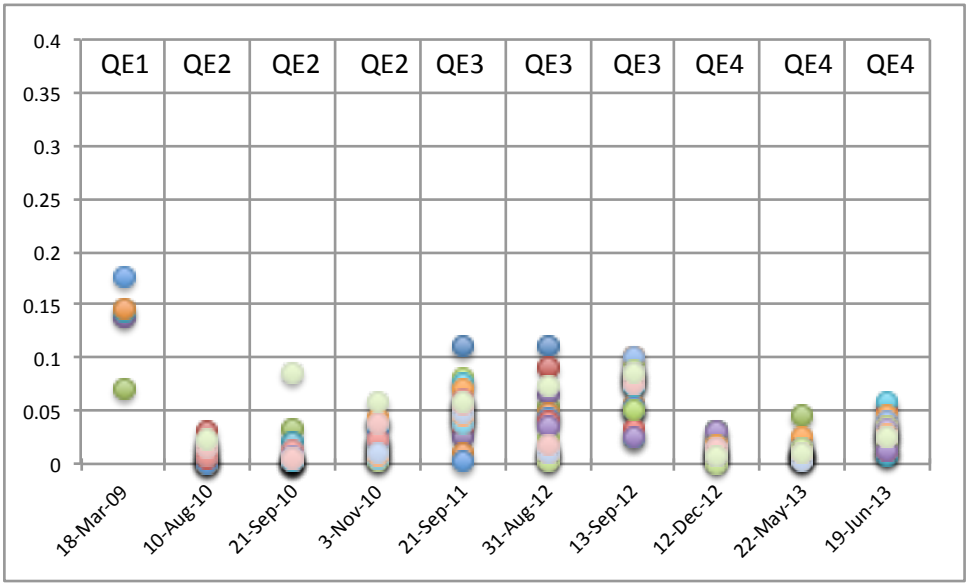


Table 4. The solvency upper bound for QE by the Fed

	Estimation method			
	Partial equilibrium		General equilibrium	
Discounting	Reduced-form	Structural	Reduced-form	Structural
Historical	19.0	16.4	13.8	19.0
Climate-change	25.8	22.5	25.8	18.7
Market-based	32.5	28.4	32.5	23.7

Notes: All numbers expressed as % of GDP