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# Quantitative Easing and the "New Normal" in Monetary Policy

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# Quantitative Easing
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## ABSTRACT

Interest rates may remain low and fall to their effective lower bound (ELB) often. As a result, quantitative easing (QE), in which central banks expand their balance sheet to lower long-term interest rates, may complement policy approaches focused on adjustments in short-term interest rates. Simulation results using a large-scale model (FRB/US) suggest that QE does not improve economic performance if the steady-state interest rate is high, confirming that such policies were not advantageous from 1960 to 2007. However, QE can offset a significant portion of the adverse effects of the ELB when the equilibrium real interest rate is low. These improvements in economic performance exceed those associated with moderate increases in the inflation target. Active QE is primarily required when nominal interest rates are near the ELB, pointing to benefits within the model from QE as a secondary tool while relying on short-term interest rates as the primary tool.



JEL Codes: E52, E47, E37

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**The analysis and conclusions set forth are those of the author and do not indicate concurrence by the Federal Reserve Board or other members of its staff.**

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Periods during which short-term nominal interest rates are stuck at their effective lower bound (ELB) may be more frequent and costly in the future, as nominal interest rates may remain substantially below the norms of the last fifty years. Using simulations of a large-scale econometric model and a dynamic-stochastic-general-equilibrium (DSGE) model, Kiley and Roberts (2017) estimate that the ELB may be encountered 40 percent of the time or more under a rule for the short-term interest rate of the type emphasized in Taylor (1999) and Yellen (2017).

During recent years, central banks provided accommodation beyond that implied by adjustments in the short-term nominal interest rates via quantitative easing (QE), in which the monetary authority purchased long-term bonds by issuing short-term liabilities (e.g., reserves). In the United States, such efforts began in late 2008.[1] Analogous programs were instituted by the Bank of England and European Central Bank (ECB) in the first half of 2009, although the magnitude of ECB purchases expanded substantially much later.[2] (Efforts in Japan had begun much earlier, reflecting the fall to the ELB in Japan by the late 1990s.) Because long-term bonds and reserves are imperfect substitutes (reflecting market-segmentation, portfolio balance, or other channels), QE lowered long-term interest rates (e.g., Gagnon et al, 2011; Ihrig et al, 2012). These declines in long-term interest rates stimulated spending, thereby supporting the economic recovery and limiting the degree to which inflation fell (e.g., Engen, Laubach, and Reifschneider, 2015).[3]

Quantitative easing is typically called an unconventional policy measure. The Federal Reserve has indicated "that changing the target range for the federal funds rate is its primary

[1] See Federal Reserve Board (2015).
[2] For a discussion of the QE program in the UK, see Joyce, Tong, and Woods (2011); for a review of the early European experience, see Altavilla, Carbon, and Motto (2015).
[3] Vayanos and Vila (2009) discuss market segmentation, and Andrés, Nelson, and Lopez-Salido (2004) embed related mechanisms in a small DGE model.

means of adjusting the stance of monetary policy", while emphasizing that it "would be prepared to use its full range of tools, including altering the size and composition of its balance sheet, if future economic conditions were to warrant a more accommodative monetary policy than can be achieved solely by reducing the federal funds rate".[4]

Research has asked whether unconventional policies should become part of the conventional toolkit, deployed regularly when recessions or disinflation warrant.[5] Some of these analyses are qualitative discussion that focus on the range of arguments offered by policymakers for or against the use of QE in the future (e.g., Bernanke, 2017). However, analysis of the systematic effects of alternative strategies for QE, accounting for the ELB, has been limited. For example, Carlstrom, Fuerst, and Paustian (2016) and Quint and Rabanal (2017) present DSGE models in which quantitative easing is a powerful instrument for counteracting financial shocks, but abstract from the interaction of quantitative easing and the ELB. Reifschneider (2016) considers the effects of QE in an illustrative scenario using the FRB/US model, but does not consider how a QE strategy interacts with the setting of the short-term interest rate under a wide variety of conditions or the relative merits of QE and other approaches, such as raising the inflation target or strategies with price-level, rather than inflation, elements. More recently, Harrison (2017) analyzes the efficacy of QE strategies in a small New-Keynesian model of the UK economy.

The analysis herein addresses this gap in the literature using a simulation approach – similar to that employed by Reifschneider and Williams (2000), Williams (2009), Coibion,

[4] These quotes are from the "Addendum to the Policy Normalization Principles and Plans" issued by the Federal Open Market Committee on June 14, 2017, available at https://www.federalreserve.gov/newsevents/pressreleases/monetary20170614c.htm.
[5] For example, Bayoumi et al (2014).

Gorodnichenko, and Wieland (2012), and Kiley and Roberts (2017). In this approach, a macroeconomic model is simulated many times, imposing the ELB, in order to assess implications of alternative strategies for the level and volatility of economic activity and inflation. In contrast to previous analyses, QE strategies are considered as complements to the strategy for the setting of the short-term interest rate. Results suggest that QE does not improve economic performance if the steady-state nominal interest rate is as high as the average value witnessed from 1960 to 2007, confirming the widely-held notion that such policies would not have been advantageous in earlier decades. However, QE can offset a significant portion of the adverse effects of the ELB when the equilibrium real interest rate is low. To achieve these benefits, QE must be both sizable and deployed quickly when economic conditions deteriorate. To achieve such gains in the simulations, active expansion of the central balance sheet is only required at times when nominal interest rates are at the effective lower bound.

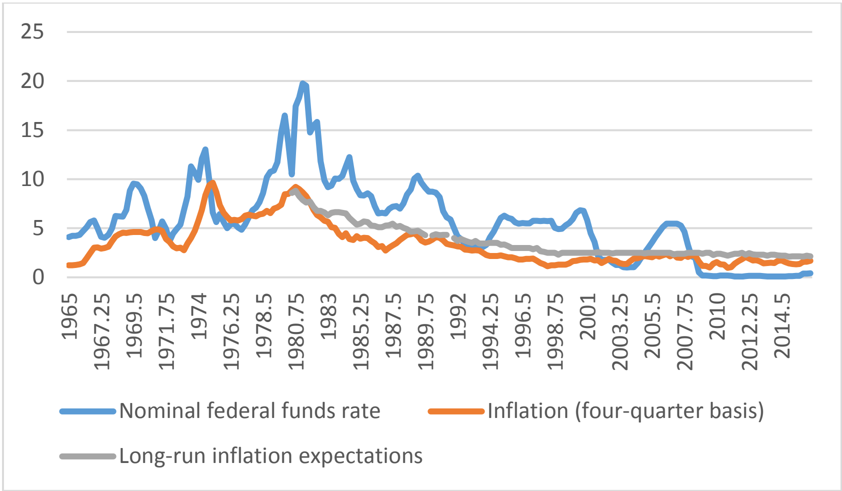
Overall, the results point to some benefits from adopting QE as a new-normal approach to monetary policy, while relying on short-term nominal interest rates as the primary tool of monetary policy.

## I. Motivation and previous research

From 1960 to 2007, the nominal federal funds rate averaged 6 percent (at an annual rate). In the decade since 2007, nominal interest rates have been much lower than this historical average in the United States (and in other advanced economies). One factor contributing to lower nominal interest rates has been the shift toward targeting a level of inflation near 2 percent – 1 percentage point below the average level from 1960 to 2007. Figure 1 graphs the evolution of the nominal effective federal funds rate, inflation, and a survey measure of long-term inflation expectations.

The downward drift in nominal rates and inflation is striking and points to the possibility that nominal interest rates may remain persistently below the averages of the past half-century.

**Figure 1: The Nominal Federal Funds Rate, Inflation, and Long-run Inflation Expectations**



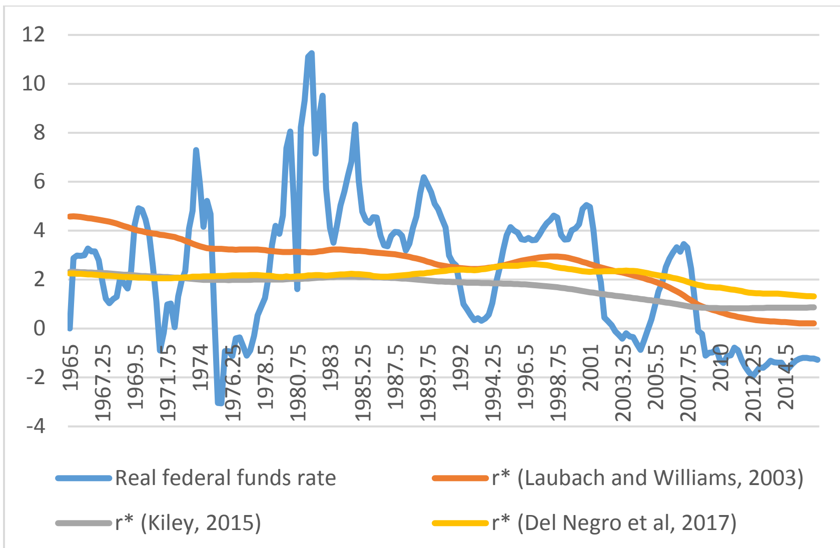

This prospect is made more likely by the possibility that structural factors have depressed the level of the (short-term) real interest rate consistent with price stability and economic activity at its potential level. Research has pointed to a number of mechanisms that may have lowered this level of the real interest rate, often referred to as the *equilibrium real interest rate r**, including a slower rate of technological progress; the demographic transitions associated with the aging of the Baby Boom, increased longevity, and changes in the dependency ratio; the overhang from an excessive buildup of household debt through the mid-2000s; and shifts in the demand for safe and liquid assets.[6]

A number of empirical studies document a decline in *r**. While there is considerable uncertainty about the current level and its future trajectory, many studies suggest that *r** may be near 1 percent (or lower) at an annual rate, 1 to 2 percentage points below the average real

[6] Discussions of factors that may contribute to a lower r* include Hamilton et al (2015), Gagnon, Johanssen, and Lopez-Salido (2016), and Eggertsson, Mehrotra, and Robbins (2017), and Del Negro et al (2017).

interest rate in the period since the middle of the last century. Figure 2 presents the evolution of the real federal funds rate since 1960 along with the estimates of *r** from the models of Laubach and Williams (2003), Kiley (2015), and Del Negro et al (2017). According to the model of Laubach and Williams (2003), *r** exceeded 3 percent from the 1960s through the 1980s and may have been as low as 0 percent in the 2010s; in contrast, the models of Kiley (2015) and Del Negro et al (2017) point to a somewhat higher value in 2016, of about 1 percent (and both studies point to smaller shifts in *r** over time than the model of Laubach and Williams, 2003)

**Figure 2: The Real Federal Funds Rate and Estimates of r***




If the inflation target is 2 percent and the equilibrium real interest rate is 1 percent, the steady-state nominal interest rate will be 3 percent. A simple thought experiment, presented in Ball (2014) and Reifschneider (2016) highlights the potential importance of such persistently lower interest rates for the frequency of the ELB and for an evaluation of the efficacy of QE strategies. In every recession since the mid-1950s, the nominal federal funds rate was reduced by more than 275 basis points, with a median reduction of more than 500 basis points. If the nominal interest rate averages 3 percent, it is reasonable to expect the ELB to bind in a recession.

Such a binding ELB will result in a deterioration of inflation and economic activity, implying that the frequency of the ELB is likely to substantially exceed the frequency of recessions in the post-WWII period in the United States.

The potential for the ELB to bind and impede economic performance, as well as policy strategies to ameliorate such effects, has been analyzed extensively since concerns regarding its effects were raised in Summers (1991). However, most research has focused on the level of the inflation target or strategies for the short-term nominal interest rate, and have not explicitly considered QE. Prior to the Great Recession, research suggested ELB episodes would be infrequent, have modest effects on economic performance, and could be mitigated by appropriate strategies.[7] Summarizing this range of pre-crisis work, Kiley, Mauskopf, and Wilcox (2007)—in a memo sent to the Federal Open Market Committee (FOMC) in 2007, 2009, and 2010—characterized the literature as suggesting the risks from the ELB to macroeconomic stability were “de minimis.”

More theoretical treatments were also relatively sanguine regarding the ELB. For example, New-Keynesian investigations of similar issues (e.g., Wolman, 1998, Eggertsson and Woodford, 2003, and Adam and Billi, 2006) emphasized how changes in the policy strategy, involving commitments akin to price-level targeting, could substantially mitigate the already modest effects of the ELB. No central bank has responded to the recent ELB episodes by adopting such an approach.

[7] For example, Reifschneider and Williams (2000), Coenen, Orphanides, and Wieland (2004), Williams (2009), and Coibion, Gorodnichenko, and Wieland (2012) considered the effects of the ELB in structural, semi-structural, and DSGE models, including the FRB/US model. These earlier studies concluded the ELB was a minor problem, in part, because the models used implied a fairly stable economy: For example, the model in Coenen, Orphanides, and Wieland (2004) implied that the standard deviation of the output gap would equal about 1 percent absent an ELB. In contrast, the Congressional Budget Office’s output gap has a standard deviation closer to 2½ percent.

Kiley and Roberts (2017) reconsider these issues, accounting for a lower equilibrium real interest rate and implementing computational improvements in imposing the ELB. They consider outcomes in a large-scale econometric model, the FRB/US model of the Federal Reserve Board, and in the DSGE model of Lindé, Smets, and Wouters (2016). Focusing on their main results using the FRB/US model, they find that the ELB will bind about 40 percent of the time and will last, on average, 2½ years if the steady-state nominal interest rate is 3 percent. Economic activity systematically falls short of potential and inflation experiences prolonged periods below target, and both activity and inflation are more volatile when the steady-state interest rate is 3 percent relative to the case where the steady-state nominal interest rate equals the 1967-2007 average of 6 percent.

Analyses of the macroeconomic effects of QE have been relatively limited and have tended not to focus on strategies for QE in a manner analogous to monetary policy strategies for interest-rate rules and the ELB.[8] For example, Chung et al (2012) and Engen, Laubach, and Reifschneider (2015) use the FRB/US model of the Federal Reserve (the model used below) to examine the impact of the QE actions from 2008 onward – but then treat these programs (essentially) as shocks to the economy and do not consider strategies, the likelihood of various outcomes, or the distribution of macroeconomic aggregates and the balance sheet of the central bank under such policy approaches. Weale and Wieladek (2014) consider analogous exercises for the United Kingdom. Sahuc (2016) proceeds similarly in analyzing the effects of the ECB's asset purchases. A significant impediment to broader work in this area is the lack of a common

[8] In contrast, the literature on the effects of QE on asset prices is larger and continues to grow rapidly. Examples include Gagnon et al (2011), Hamilton and Wu (2012), D'Amico, English, Lopez-Salido and Nelson (2012), Li and Wei (2012), and Rogers, Scotti and Wright (2014).

framework with which to model the transmission channels through which QE affects spending and inflation.[9] Carlstrom, Fuerst, and Paustian (2016) and Quint and Rabanal (2017) present alternative DSGE models of how QE affects financial markets and analyze interest-rate or balance-sheet rules, but do not consider the ELB.

A recent investigation more akin to the focus herein is presented in Reifschneider (2016), which provides illustrative simulations in which policymakers confronted by a severe U.S. recession act to combat the economic downturn by augmenting a conventional response (akin to the simple interest rate rule of the type analyzed below) through a combination of forward guidance and quantitative easing. These simulations suggest roles for forward guidance—which will also be considered in the section on commitment strategies—and quantitative easing. However, these simulations focus only on developments following an individual shock and starting from steady-state initial conditions, and hence cannot discuss the frequency of QE expansions, the resulting effect on macroeconomic aggregates, and the size and variability of the central bank's balance sheet under alternative strategies. Moreover, alternative mitigation strategies, such as raising the inflation target of strategies akin to price-level approaches, are not considered. Our simulation approach, discussed in the next section, allows consideration of these issues.

[9] For example, DSGE models often assume market segmentation as a key channel through which QE affects spending, and estimated versions of such models have not found that QE is as potent as has been assumed in large-scale econometric models (see Chen, Curdia, and Ferrero (2012) and Kiley (2014a)). In contrast, both DSGE and large-scale econometric models tend to share a common framework for the transmission of adjustments in the short-term interest rate, as discussed in Boivin, Kiley, and Mishkin (2010).

## II. The modeling approach

The analysis uses the FRB/US model maintained by the Federal Reserve Board staff. This model is used to analyze the frequency and consequences of ELB episodes in Reifschneider and Williams (2000), Williams (2009), and Kiley and Roberts (2017); it provided the estimates of the effects of QE on the U.S. economy following 2008 in Chung et al (2012) and Engen, Reifschneider, and Laubach (2015); and Reifschneider (2016) employed the FRB/US model to illustrate the ability of QE to address a recessionary shock starting from steady-state conditions.

As emphasized in Brayton, Laubach, and Reifschneider (2014), the FRB/US model of the U.S. economy is one of several that Federal Reserve Board staff consults for forecasting and the analysis of macroeconomic issues, including both monetary and fiscal policy. The model is large relative to DSGE models, and its equations are linked to core macroeconomic frameworks, such as the permanent-income model of consumption and the neoclassical user-cost model of investment, but are not closely tied to representative-agent optimization problems as in DSGE models. Importantly, the FRB/US model includes inertial behavior in many of its spending, as well as price and wage, equations—through inclusion of adjustments costs that introduce a longer lag structure into the dynamic specification of the model than in smaller DSGE models. In addition, a number of key frictions are incorporated in the empirical specification, including a role for liquidity-constrained and unconstrained households, disaggregated equations for firms' investments in durable equipment, intellectual property, and nonresidential structures that include *ad hoc* accelerator terms that may capture the effects of sales on liquidity-constrained firms' ability to invest. Finally, a variety of interest rates, including yields on Treasury securities, corporate bond yields, and residential mortgage rates, are determined as the expected average value of the federal funds rate over the appropriate holding period plus endogenous term/risk premiums; equity prices equal the present discounted value of corporate earnings based on an estimated require return to equity; and monetary policy is modeled as a simple rule for the federal funds rate subject to the zero lower bound on nominal interest rates.

The role of long-term interest rates in monetary-policy transmission is important in any assessment of the macroeconomic effects of QE. The FRB/US model places yields on long-term Treasury securities at the center of monetary transmission, implying important roles for both the expected sequence of short-term interest rates (the expectations hypothesis component of long-term Treasury yields) and term premiums (or, in the FRB/US model, the residual component after removing the expected short rates from Treasury yields). To offer three examples, the market value of equity wealth, an important determinant of household spending in the model, is tied to a 30-year Treasury yield plus a risk premium; corporate bond yields and mortgage rates are modeled as 10-year Treasury yields plus a risk premium, and are the interest rates that affect business and residential investment; and the interest rate affecting consumer durable purchases is tied to a 5-year Treasury yield. Note that in each case the relationships between these interest rates and spending decisions are estimated, although the ties to Treasury yields are largely assumed in the model's construction.

Because of the link between Treasury yields, interest rates facing households and businesses, and private spending, QE can affect spending and inflation by influencing the path of term premiums and hence Treasury yields. Following Engen, Laubach, and Reifschneider (2015) and Reifschneider (2016), I adopt estimates of the effect of quantitative easing on Treasury yields from earlier work which suggest purchases of 10-year Treasury securities of $500 billion (financed with an expansion of short-term liabilities or reduction of short-term assets held by the Federal Reserve) lower the 10-year term premium by 20 basis points (along with 17bp and 7bp declines in the term premiums on 5-year and 30-year Treasury securities). For example, Ihrig et al (2012) suggest that the maturity extension programs (MEP I and MEP II, initiated in September 2011 and June 2012, respectively) involved purchases of $400 and $267 billion in long-term Treasury securities (financed by sales of short-term securities) and lowered the 10-year term premium by 17 basis points and 11 basis points, respectively, consistent with 20bp per $500 billion in purchases. The survey in Gagnon (2016), covering 16 studies of the effects of asset purchases on Treasury yields in the United States, suggests a central tendency for the effect of $500 billion in purchases of between 20 and 30 basis points, similar to the value used herein.

A couple of points are important regarding the effects of QE on financial conditions assumed in our analysis and in Reifschneider (2016). First, the impact effects are about twice as large, on a per-dollar basis, as in LSAP I and II. In addition, the effects last several years, whereas Wright (2012) and Swanson (2017) present evidence consistent with more short-lived effects. Moreover, the FRB/US model assumes that effects on Treasury term premiums pass through to corporate bonds, mortgage rates, equity prices, and the exchange value of the dollar by a similar magnitude as expected short-term interest rates, whereas preferred habitat models such as Vila and Vayanos (2009) predict more limited pass-through. Engen, Laubach, and Reifschneider (2015) review the literature as of their study and find that the pass-through effects in the FRB/US model were within the reasonable range, while Kiley (2014b, 2016a) presents evidence consistent with the limited pass-through predicted by economic theory. Finally, some DSGE models (Chen, Curdia, and Ferrero, 2012; and Kiley, 2014a) have a more limited role for term premiums than expected short rates. For all of these reasons, our analysis may overstate the effects of QE on macroeconomic activity. Nonetheless, the analysis uses these assumptions because they are most similar to earlier studies (Engen, Laubach, and Reifschneider, 2015; and Reifschneider, 2016).

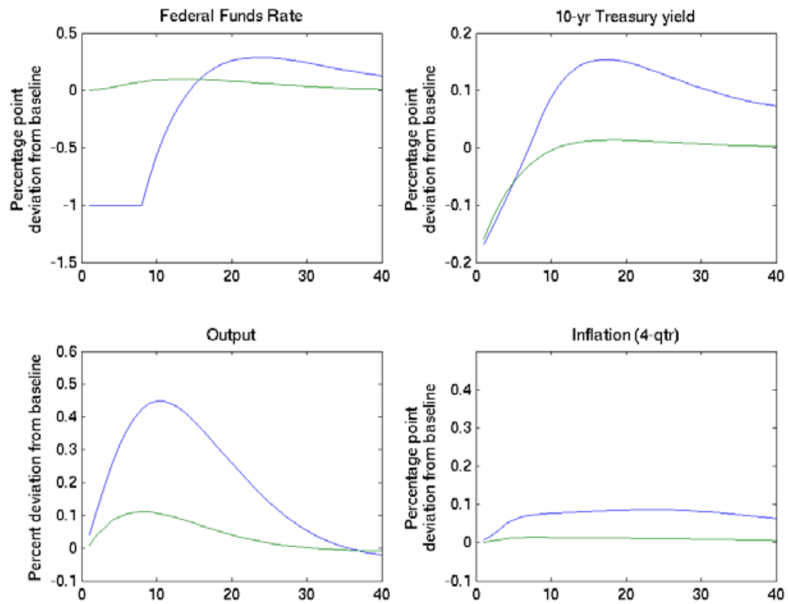
To illustrate the effects of both changes in the short-term interest rate and QE on Treasury yields, economic activity, and inflation, I present impulse responses to a path in which the short-term interest rate is cut and to a $500 billion purchase of Treasury securities by the FOMC in figure 3. For the interest rate shock, I assume that the nominal federal funds rate is reduced (relative to a baseline) by 100bp for eight quarters and subsequently follows the policy rule from English, Lopez-Salido, and Tetlow (2015), given in equation 1 (where constant terms are suppressed).

$$i(t) = .85i(t-1) + 0.15\left(1.5\pi^4(t) + y(t)\right) \quad \textbf{(1)}$$

For quantitative easing, I assume an immediate one-time purchases of $500 billion in long-term Treasury securities, with this stock of asset holdings decaying toward baseline at a rate of 0.05 percent per quarter. The assumption that balance-sheet expansions follow this persistent pattern after reaching their peak is consistent with assumption in Ihrig et al (2012) and Reifschneider (2016) – each of which considers the paths embedded in views among the public of the Federal Reserve’s actions in the years following 2008.

As can be seen in the upper right panel, both monetary policy actions lower long-term Treasury yields by a bit less than 20bps on impact. Note that this effect is less than the direct effect of the 8-quarter decline in the nominal funds rate on a zero-coupon 10-year Treasury security or the assumed impact effect of $500 billion in QE on the 10-year Treasury yield, both of which equal 20bps. This difference arises because the endogenous subsequent reaction of the federal funds rate involves a tightening of monetary policy in response to the increase in output and inflation.

**Figure 3: Effect of Reductions in Federal Funds Rate and $500 Billion QE**




As can be seen clearly in the lower right panel, output rises by substantially less in response to the QE program than following the cut in the federal funds rate, despite the similar effects on the 10-year Treasury yield. This occurs because the 10-year Treasury yield is not the only important interest rate in the FRB/US model. For example, both the 5-year and 30-year Treasury yields influence household and business spending in the FRB/US model, and there are also direct effects of short-term interest rates. Such roles for a range of interest rates are consistent with economic theory—different rates play different roles in models with segmented markets or other types of imperfect substitution, and hence all interest rates are important for economic activity (at least to some degree, e.g., Kiley, 2014a). In terms of magnitudes, the response of output to the change the Treasury term premium associated with QE are modest, similar to that in Reifschneider (2016), and the response to changes in the federal funds rate is similar to that in Laforte and Roberts (2014) for the FRB/US model.[10]

The limited effects of QE in these simulations would seem to imply that such actions would need to be fairly sizable to systematically offset any adverse effects associated with the ELB in practice. The next section considers this issue.

## III. Economic performance under rules for short-term interest rates

### III.a Our simulation approach

Much of our analysis will involve computation of moments from simulations of the FRB/US. In computing these simulations, I adopt an approach similar to that in Reifschneider and Williams (2000), Williams (2009), and Kiley and Roberts (2017). In particular, the simulations

- Generate 500 simulated samples of 200 periods (e.g., 40 years), initializing the simulations at the models' non-stochastic steady state.
- Impose the ELB appropriately under alternative assumptions about the steady-state nominal interest rate.
- Draw shocks from the period 1970 to 2015 for the FRB/US (via a bootstrap of the residuals from the model). I assume no shocks to monetary policy—monetary policy strictly follows the rules I posit below for the short-term nominal interest rate and QE.

[10] Reifschneider (2016) reports that the unemployment rate falls a bit less than ½ percentage point for $4 trillion in asset purchases, under a feedback rule for the federal funds rate that is optimal in the FRB/US model for the loss function he assumes, implying a decline in the unemployment rate of less than 0.0625 and, via Okun's law, a decline in output of about 0.1 percentage point per $500 billion in QE. This is essentially identical to the estimate in figure 3. Laforte and Roberts (2014) report responses for a 1-period increase in the federal funds rate, and the movements in output in the version of FRB/US used herein are essentially identical to those they report.

- Impose the ELB as in Williams (2009). I assume that agents never expect the ELB to bind for more than 15 years.[11]
- I assume that agents have model-consistent expectations. As a consequence, households and firms fully understand the policy regime that is in place.[12]

An important element of the stochastic simulations I perform is that they do not rely on assessing outcomes relative to a given set of initial conditions – as in the analysis of shocks relative to steady-state conditions in previous work on the ELB or QE (e.g., the simulation approach of Eggertsson and Woodford, 2003; Reifschneider and Roberts, 2006; and Reifschneider, 2016). As Kiley and Roberts (2017) emphasize, especially adverse outcomes may arise following back-to-back recessions, as the United States experienced in the early 1980s, and the stochastic simulation approach allows this possibility. This advantage is important for assessing likely behavior across the business cycle and over time.

### III.B. Performance under an estimated and a simple rule

Our analysis begins with the simulation outcomes from the FRB/US model under an estimated policy rule and a simple rule of the Taylor (1993, 1999) form, using the coefficients from what Yellen (2017) terms a balanced approach. Under the estimated rule, the federal funds rate is set by the following equation (suppressing constants, with the coefficients estimated for the 1988-2007 period using data from the CBO on the output gap),

[11] This is an improvement, built on the work of Kiley and Roberts (2017), relative to earlier work. For example, Williams (2009) assumed that the ELB only strictly binds (in expectation) for up to 4 years.

[12] In the absence of QE, I include an emergency fiscal stimulus package that is enacted when the output gap is lower than -10 percent. This fiscal package is implemented as an expansion of government purchases, and prevents the emergence of extremely bad outcomes. A similar approach is followed in Reifschneider and Williams (2000), Williams (2009), and Kiley and Roberts (2017). The fiscal stimulus package is fairly rare and results would largely be the same without this assumption.

$$i(t) = .9i(t-1) + .2\pi^4(t) + .15y(t) + .25\Delta y(t) \quad \textbf{(2)}$$

where $i(t)$ is the nominal interest rate (at an annual rate), $\pi^4(t)$ is the four-quarter percent change in the core PCE price index, and $y(t)$ is the output gap, measured as the deviation of output from productive potential as gauged by the production function in the FRB/US model.

Table 1 presents historical statistics for the output gap (as measured by 100 times the natural logarithm of real GDP divided by the CBO's estimate of potential), core PCE inflation (measured on a four-quarter basis), and the nominal federal funds rate, along with statistics from stochastic simulations of the FRB/US model assuming that the steady-state nominal interest rate equals 6 percent (the 1960-2007 average) and the effective lower bound is zero; these results were previously reported in Kiley and Roberts (2017). The statistics from the FRB/US model are broadly similar to their sample counterparts—although inflation is slightly less volatile (with a standard deviation of 1.5 percentage points, whereas the sample counterpart from 1960-2007 equals 2.2 percentage points). The ELB rarely binds for a steady-state nominal interest rate of 6 percent.

**Table 1: Standard Deviations of the Output Gap, Inflation, and Federal Funds Rate**

| | Standard deviations of variables | | |
|---|---|---|---|
| | Output gap | Core inflation | Nominal federal funds rate |
| **Maximum History** | 2.5 | 2.2 | NA |
| **1960-2007** | 2.3 | 2.2 | 3.3 |
| **1984-2007** | 1.4 | 1.0 | 2.4 |
| **Model under estimated rule and steady-state nominal interest rate of 6 percent** | | | |
| **FRB/US** | 2.2 | 1.5 | 2.8 |
| **FREQUENCY OF ELB IN MODEL SIMULATIONS** | | | |
| **FRB/US** | 2.0 percent | | |

Outcomes from the model simulations in table 1 assume that the steady-state nominal interest rate equals 6 percent. With an inflation target of 2 percent and estimates of the long-run real federal funds rate from recent studies between 0 and 1 percent, it is reasonable to consider outcomes under far lower steady-state nominal interest rates. For concreteness, I assume that the inflation target is 2 percent and the equilibrium real interest rate $r^*$ is between 0 and 3 percent, consistent with the evidence reviewed above. As a result, our discussion will focus on the steady-state nominal interest rates from 2 percent up to the historical average of 6 percent.

Table 2 presents outcomes from stochastic simulations for alternative values of the steady-state nominal interest rate under the estimated rule (top panel) and under the balanced-approach specification of the Taylor (1993, 1999) rule (bottom panel), specified as

$$i(t) = r^* + 2 + 1.5(\pi^4(t) - 2) + y(t). \quad \textbf{(3)}$$

**Table 2: Performance under Estimated and Simple Rules for Alternative Values of the Steady-State Nominal Interest Rate**

| | ELB frequency | Mean duration of ELB | mean(y) | mean(π) (π*=2) | RMSD(y) | RMSD(π) |
|---|---|---|---|---|---|---|
| | | | **Estimated rule (2)** | | | |
| **6** | 2.0 | 5.4 | 0.0 | 2.0 | 2.2 | 1.5 |
| **5** | 5.1 | 5.8 | -0.1 | 1.9 | 2.4 | 1.5 |
| **4** | 12.8 | 8.3 | -0.4 | 1.7 | 2.7 | 1.7 |
| **3** | 31.7 | 9.2 | -1.3 | 1.2 | 3.7 | 2.1 |
| | | | **Simple rule (3)** | | | |
| **6** | 5.3 | 4.5 | -0.1 | 2.0 | 2.3 | 1.6 |
| **5** | 10.0 | 5.5 | -0.1 | 1.9 | 2.4 | 1.6 |
| **4** | 20.2 | 7.8 | -0.4 | 1.7 | 2.8 | 1.8 |
| **3** | 38.3 | 9.8 | -1.1 | 1.2 | 3.4 | 2.2 |

An analysis of outcomes under the simple rule is useful for several reasons. First, its simple form relates the current level of the nominal interest rate to the deviations of inflation from target and output from potential, and therefore captures both goals of a dual-mandate central bank. In addition, previous research has shown such rules produce reasonable economic performance abstracting from the effective lower bound (e.g., Taylor and Williams, 2010). Finally, it is a benchmark often consulted within the Federal Reserve, including through regular presentations in the discussion of monetary policy alternatives in material produced for the FOMC (e.g., Tealbook B) and as represented by calculators available at Federal Reserve Banks.[13] Overall, the results suggest that both the estimated and the simple rules are ineffective at addressing the challenges that arise if the steady-state nominal interest rate lies below 4 percent. In the FRB/US model, inflation and output systematically fall short of their objectives when the steady-state nominal interest rate equals 3 percent. Moreover, the ELB binds nearly 2/5th of the time and the mean duration of ELB episodes is 2½ years under the simple rule (and the duration of episodes is highly positively skewed, implying some episodes are much longer). Of note, the mean shortfall of output from potential of more than 1 percent per year under both policy rules for a steady-state real interest rate of 1 percent implies a present-discounted value of lost output that exceeds an entire year's GDP – that is, more than $18 trillion dollars in 2016.

## IV. Economic performance under rules for QE

The strategies considered above involve only adjustments to the short-term nominal interest rate. How much improvement in economic outcomes could be achieved through systematic use of

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[13] Materials prepared by staff for the Federal Open Market Committee began regularly reporting the prescriptions from this rule in advance of decisions in January 2004 and have continued to report these prescriptions through the most recent publicly available materials (in the "Bluebook" and "Tealbook B"; see https://www.federalreserve.gov/monetarypolicy/fomchistorical2004.htm). The Taylor-rule utility at the Federal Reserve Bank of Atlanta can be found at https://www.frbatlanta.org/cqer/research/taylor-rule.aspx?panel=1; the Taylor-rule utility at the Federal Reserve Bank of Cleveland can be found at https://www.clevelandfed.org/en/our-research/indicators-and-data/simple-monetary-policy-rules/about.aspx.

QE? To investigate this possibility, I consider several such systematic approaches, each of which differs in the degree to which QE is employed.

### IV.A An asymmetric QE approach

QE has been actively deployed to fight an economic downturn, and the FOMC has communicated that it generally intends to follow a passive approach to decreasing its balance sheet (FOMC, 2017). The general approach to a QE rule adopted to match these patterns in the simulations has two elements:

- QE is only first deployed when interest rates fall to their effective lower bound and economic activity is sufficiently below potential.
- QE is asymmetric, with active purchases of assets when the economy is weak and a passive runoff of these holdings when economic activity is stronger. This approach follows the general description of how the FOMC has pursued QE in the past, as described by Bernanke (2017).
- QE is implemented gradually—asset purchases rise from an initial inception point and are subsequently (passively) runoff.

These ideas are operationalized via two assumptions.

First, the fluctuations of the size of the Federal Reserve's balance sheet (relative to its steady-state level, denoted QE(t)) are governed by an autoregressive (AR) process of order 2

$$QE(t) = 1.6QE(t-1) - 0.62QE(t-2) + AP(t) \quad \textbf{(4)}$$

where AP(t) denotes the "shock" to asset purchases in period t. According to this process, the stock of assets associated with a QE program peaks one year following initiation of the program at a level twice the size of the initial shock, remains near this level for several quarters, and subsequently runs off at a rate of about 0.05 percent per quarter. These features accord reasonably well with the notion that previous increases in the balance sheet by the Federal Reserve took place over a year or more and with the pace of unwinding assumed in Reifschneider (2016). In the implementation herein, the effects of QE on term premiums are proportional to the current level of the central bank's balance sheet, and hence the term premium dynamics associated with QE follow the same pattern as the balance sheet. As a result, the dynamics of the term premium – the variable through which QE affects activity and inflation in FRB/US – are identical to those in Reifschneider (2016) following a QE impulse.

Second, the initiation of purchases follows one of the four cases outlined in table 3, which differ in their intensity.

**Table 3: Alternative QE rules**

| | |
|---|---|
| **QE A:** Initiation of purchases (AP(t)) when **r(t)<0.25 & y(t)<-5** at a rate of **$25 billion** per quarter per unit of y(t)<-5, implying approximately **$500 billion in QE** if the output gap equals -7.5 for four quarters | **QE C:** Initiation of purchases (AP(t)) when **r(t)<0.25 & y(t)<-2.5** at a rate of **$25 billion** per quarter per unit of y(t)<-2.5, implying approximately **$1 trillion in QE** if the output gap equals -7.5 for four quarters |
| **QE B:** Initiation of purchases (AP(t)) when **r(t)<0.25 & y(t)<-5** at a rate of **$50 billion** per quarter per unit of y(t)<-5, implying approximately **$1 trillion in QE** if the output gap equals -7.5 for four quarters | **QE D:** Initiation of purchases (AP(t)) when **r(t)<0.25 & y(t)<-2.5** at a rate of **$50 billion** per quarter per unit of y(t)<-2.5, implying approximately **$2 trillion in QE** if the output gap equals -7.5 for four quarters |

In all cases, asset purchases are initiated (AP(t)>0) only if the short-term nominal interest rate falls to zero and a condition for activity is met. In the first column, a QE program is initiated during any quarter when the output gap falls below -5 percent, whereas column 2 raises the threshold for action to an output gap of -2.5 percent. (Note that programs can be initiated in back-to-back quarters – that is, AP(t) can be positive in back-to-back quarters.) Rows 1 and 2 differ in the pace of QE – with the bottom-right cell, called **QE D** representing the most aggressive constellation considered, in which the balance sheet expands by roughly $2 trillion if the output gap falls to -7.5 percent for four quarters (given the dynamics implied by the AR process).[14]

Our simulations proceed in the same manner as those in the previous section, and our analysis focuses on the case in which the four alternative QE programs above complement the simple rule for the federal funds rate (the balanced approach rule). Table 4 presents results for each QE approach, with the top rows repeating results in the absence of QE under the simple rule. Several results emerge from this analysis. First, there is little advantage to deploying QE when the steady-state nominal interest rate is near the average level of the federal funds rate from 1960 to 2007 of 6 percent. Under each QE approach, the volatility of economic activity and inflation is essentially the same in the absence of QE and with QE when the steady-state nominal interest rate equals 6 or 5 percent. Moreover, the average level of economic activity essentially equals potential and inflation averages its target rate of 2 percent. Additionally, the frequency and duration of episodes at the ELB is roughly the same in the presence or absence of QE.

[14] Implementation of these threshold rules for QE involves some technical assumptions that reflect a compromise between practical considerations that allow an analysis of the issues. In particular, I make the assumption that agents do not anticipate the initiation of a QE program, but fully take into account its trajectory (in a manner consistent with the model dynamics) subsequent to its initiation. As a result, precautionary are not incorporated, and expectation effects may be only partly incorporated. This is common in approximations of models with occasionally-binding constraints: For example, the algorithm of Guerrieri and Iacoviello (2015) has this feature, and those authors take care to compare their approximate solution method to an exact solution for cases where such comparisons can be made. Given the size and complexity of the FRB/US model, I cannot consider the accuracy of the approximation herein to a solution that fully accounts for expectation and precautionary effects. That said, two factors suggest our conclusions may accurately reflect the effects of QE as embedded in the FRB/US model. First, the transmission channel for QE arises through effects on term premiums, and the effects of term premiums in the FRB/US model enter contemporaneously or via lags – so direct expectation effects are not important. Second, an appendix considers a symmetric QE rule below in which expectation effects are more fully incorporated and reach very similar conclusions to those found when threshold rules for QE are used.

### Table 4: Performance under Alternative QE Approaches

| | ELB frequency | Mean duration of ELB | mean(y) | mean(π) (π*=2) | RMSD(y) | RMSD(π) |
|---|---|---|---|---|---|---|
| **Simple rule for nominal interest rate without QE** | | | | | | |
| **6** | 5.3 | 4.5 | -0.1 | 2 | 2.3 | 1.6 |
| **5** | 10 | 5.5 | -0.1 | 1.9 | 2.4 | 1.6 |
| **4** | 20.2 | 7.8 | -0.4 | 1.7 | 2.8 | 1.8 |
| **3** | 38.3 | 9.8 | -1.1 | 1.2 | 3.4 | 2.2 |
| **2** | 60 | 11.2 | -2 | 0.5 | 4.1 | 2.7 |
| **QE A: Initiation of purchases (AP(t)) when r(t)<0.25 & y(t)<-5 at a rate of $25 billion per quarter per unit of excess output gap** | | | | | | |
| **6** | 5.1 | 4.4 | 0 | 2 | 2.3 | 1.6 |
| **5** | 9.5 | 5.2 | -0.1 | 1.9 | 2.4 | 1.6 |
| **4** | 17.9 | 7.0 | -0.3 | 1.8 | 2.6 | 1.7 |
| **3** | 32.5 | 10.1 | -0.7 | 1.5 | 3.0 | 1.9 |
| **2** | 52.4 | 13.3 | -1.3 | 1 | 3.5 | 2.1 |
| **QE B: Initiation of purchases (AP(t)) when r(t)<0.25 & y(t)<-5 at a rate of $50 billion per quarter per unit of excess output gap** | | | | | | |
| **6** | 5.0 | 4.4 | 0 | 2 | 2.3 | 1.6 |
| **5** | 9.2 | 5.0 | -0.1 | 2 | 2.4 | 1.6 |
| **4** | 16.8 | 6.6 | -0.2 | 1.8 | 2.5 | 1.6 |
| **3** | 29.8 | 9.2 | -0.5 | 1.6 | 2.9 | 1.8 |
| **2** | 48.0 | 13.7 | -1 | 1.2 | 3.3 | 2.0 |
| **QE C: Initiation of purchases (AP(t)) when r(t)<0.25 & y(t)<-2.5 at a rate of $25 billion per quarter per unit of excess output gap** | | | | | | |
| **6** | 4.7 | 4.3 | 0 | 2.0 | 2.3 | 1.6 |
| **5** | 8.6 | 4.8 | 0 | 2.0 | 2.3 | 1.6 |
| **4** | 15.6 | 6.3 | -0.1 | 1.9 | 2.5 | 1.6 |
| **3** | 27.1 | 8.5 | -0.3 | 1.7 | 2.8 | 1.7 |
| **2** | 44.2 | 12.8 | -0.8 | 1.4 | 3.1 | 1.9 |
| **QE D: Initiation of purchases (AP(t)) when r(t)<0.25 & y(t)<-2.5 at a rate of $50 billion per quarter per unit of excess output gap** | | | | | | |
| **6** | 4.4 | 4.1 | 0 | 2.0 | 2.3 | 1.6 |
| **5** | 7.9 | 4.6 | 0 | 2.0 | 2.3 | 1.6 |
| **4** | 13.9 | 5.7 | 0 | 2.0 | 2.4 | 1.6 |
| **3** | 23.3 | 7.4 | -0.1 | 1.9 | 2.6 | 1.6 |
| **2** | 37.3 | 10.6 | -0.4 | 1.7 | 2.8 | 1.7 |

Second, QE provides clear benefits when the steady-state nominal interest rate is low, especially when the steady-state nominal interest rate is as low as 3 or 2 percent, the value consistent with recent estimates of the equilibrium real interest rate and an inflation target of 2 percent. The improvement in economic performance is smaller for the approaches that imply less QE: For example, the **QE A** approach, the smallest approach considered, implies an improvement, with the average shortfall of economic activity relative to potential equaling -0.7 percent rather than -1.1 percent when the steady-state nominal interest rate equals 3 percent.

This gain is sizable. At a real interest rate of 1 percent, a gain in economic activity of 1/3 percentage point equates to a present value in excess of $6 trillion dollars for the 2016 value of gross domestic product. But the gain is much smaller than that associated with the more aggressive QE D policy.

Third, a comparison of the QE B and QE C approaches to the QE A approach shows benefits from both responding more forcefully in dollar terms once a threshold is reached and to having a higher threshold (e.g., acting sooner when output declines) for activation of QE. In particular, the QE B program is activated only after the output gap falls below -5 percent, but has a larger pace of purchases, whereas the QE C program is activated when output falls below -2.5 percent at a slower rate of purchases. While both approaches imply greater stability, output closer to potential on average, and inflation closer to the 2 percent target on average, the early initiation of QE – the QE C policy – performs marginally better than the late initiation of QE at a faster pace of purchases. This points to some benefit of adopting QE as a new-normal approach to monetary policy if the steady-state nominal interest rate is as low as suggested by evidence in Holston, Laubach, and Williams (2016), Kiley (2015), and Del Negro et al (2017).

Indeed, our final takeaway from table 4 is that the benefits of regular deployment of QE during economic downturns may be substantial if such actions are initiated quickly and at a robust pace, as under the QE D approach. As highlighted in the penultimate row of table 4, the volatility of inflation and output remains much closer to the 1960-2007 experience when QE is deployed regularly and forcefully even if the steady-state nominal interest rate is 3 percent. Moreover, the average shortfall of output relative to potential is only -0.1 percent – 1 percentage point higher than under the simple rule alone (the fourth row in the top part of table 4). The present-discounted value of this gain exceeds $18 trillion dollars at the 2016 value of U.S. gross domestic product.

Examination of the distribution of the central bank's balance sheet under each of the QE approaches is informative in thinking about the degree to which the alternative strategies imply large asset purchases. Table 5 presents key characteristics of the distribution of asset holdings by the central bank relative to the steady state for the case of a steady-state nominal interest rate of 3 percent. Note these statistics are in trillions of dollars and apply to a steady state in which the US economy is its size around 2015 – and hence these figures would rise in the future with the size of the economy.

**Table 5: Key Characteristics of the Distribution of Asset Holdings Under Alternative QE Approaches When Steady-State Nominal Interest Rate Equals 3 percent**

| Median size | Mean size | 75th percentile | 90th percentile | 95th percentile | Percent $\Delta QE(t)>0$ & $i(t)>0.25$ |
|---|---|---|---|---|---|
| QE A | | | | | |
| $1 billion | $225 billion | $71 billion | $642 billion | $1.39 trillion | 16.2 |
| QE B | | | | | |
| $1 billion | $332 billion | $106 billion | $947 billion | $2.09 trillion | 16.2 |
| QE C | | | | | |
| $59 billion | $438 billion | $391 billion | $1.37 trillion | $2.35 trillion | 6.6 |
| QE D | | | | | |
| $90 billion | $613 billion | $567 billion | $1.87 trillion | $3.21 trillion | 6.7 |

The magnitudes in table 5 are not outsized relative to the QE programs initiated following the Great Recession. Even the most aggressive program involves an upper tail (95th percentile) for the size of the central bank's balance sheet that reaches $3.2 trillion dollars, in the ballpark of the increases in the Federal Reserve's balance sheet during its QE efforts beginning in late 2008. The simulation results suggest that a future strategy of this type – if implemented and according to the calibrated effects of QE in the FRB/US model – could mitigate the most adverse effects of the ELB. Note that these benefits arise even though QE is restricted to be a secondary tool, deployed only after the short-term nominal interest rate has fallen to zero.

## V. Comparison of QE to commitment strategies or a higher inflation target

While QE was adopted by many central banks that hit the ELB over the past decade, academic research has pointed other approaches to dealing with ELB risks: Commitments to overshoot inflation or activity objectives in the future in order to stimulate inflation and activity today—that is, forward guidance of the Odyssean variety in the lexicon of Campbell, Evans, Fisher, and Justiniano (2012); or a higher inflation target, as suggested by Ball (2014).

To compare these policy approaches to QE, I compare simulated outcomes for economic activity and inflation under the most aggressive QE strategy analyzed above (QE D) with those for a higher inflation target or an example of a commitment approach. For the latter, I adopt a commitment strategy previously examined in Kiley and Roberts (2017) involving a policy rule in which the change in the nominal interest rate responds to the deviation of inflation from an inflation objective of 2 percent and the output gap. In addition, the approach assumes a commitment to remain more accommodative following a period in which the ELB binds through a strategy which keeps track of the "shadow" rate of interest—that is, the interest rate that would have prevailed had the ELB not applied—and which does not raise interest rates until this shadow rate rises above the effective lower bound. Algebraically, I can define the shadow rate, $i^*$, as

$$i^*(t) = .125(\pi^4(t) - 2) + .125y(t) + i^*(t-1), \quad \textbf{(5)}$$

The policy rate is then set equal to the maximum of this shadow rate and the ELB:

$$i(t) = \max(i^*(t), i^{ELB}). \quad \textbf{(6)}$$

Under this rule, the shadow rate will continue to fall if output and inflation fall below objective during an ELB episode, and the nominal interest rate will not rise above the ELB until the shadow rate rises above the ELB.

The rule embeds several commitment elements. First, the policy rate will not be lifted above zero until either inflation or output overshoot their objective (because it is the change in the shadow rate that is linked to inflation and the output gap, and hence the change in the actual nominal policy rate cannot be positive until at least one of these variables overshoot objective). Second, the shadow rate accumulates foregone accommodation associated with the ELB and does not lift above zero until this accumulated foregone accumulation has been run off. This mechanism is related to the one proposed by Reifschneider and Williams (2000), who suggested that policymakers keep track of the foregone decline in interest rates implied by an ELB and commit not to raise the short-term policy rate above the ELB until this stock of forgone cuts in interest rates has been exhausted. Coibion, Gorodnichenko, and Wieland (2012) employ a similar shadow rate adjustment, and this commitment assumption is central to their finding that the ELB is only mildly binding in their DSGE model. Finally, the proposed rule has a price-level element absent the ELB. Integrating backward, the rule can be rewritten as:

$$i(t) = .125\left\{\sum_{i=0}^{3}(p(t-i) - .5t) + \sum_{j=0}^{\infty} y(t-j)\right\}^{15}, \tag{7}$$

Here, the rule responds to the average of the price-level over the most recent four quarters relative to a trend that increases at a 2 percent (annual rate) per period, as well as to the entire history of deviations of output from potential. A simple version of the first component of the rule (e.g., the current price level) is shared with price-level targeting and nominal-income targeting rules. The second component would not be present in a pure price-level rule; in a nominal-income targeting rule, only the current value of the output gap would be present, not the entire history of output gaps. Rules that include a price-level element, as in the shadow-rate version of our rule, have been shown to be quite valuable in stabilizing the economy and have been discussed as a potential commitment approach, especially in discussions of the effective lower bound (Woodford, 2003).

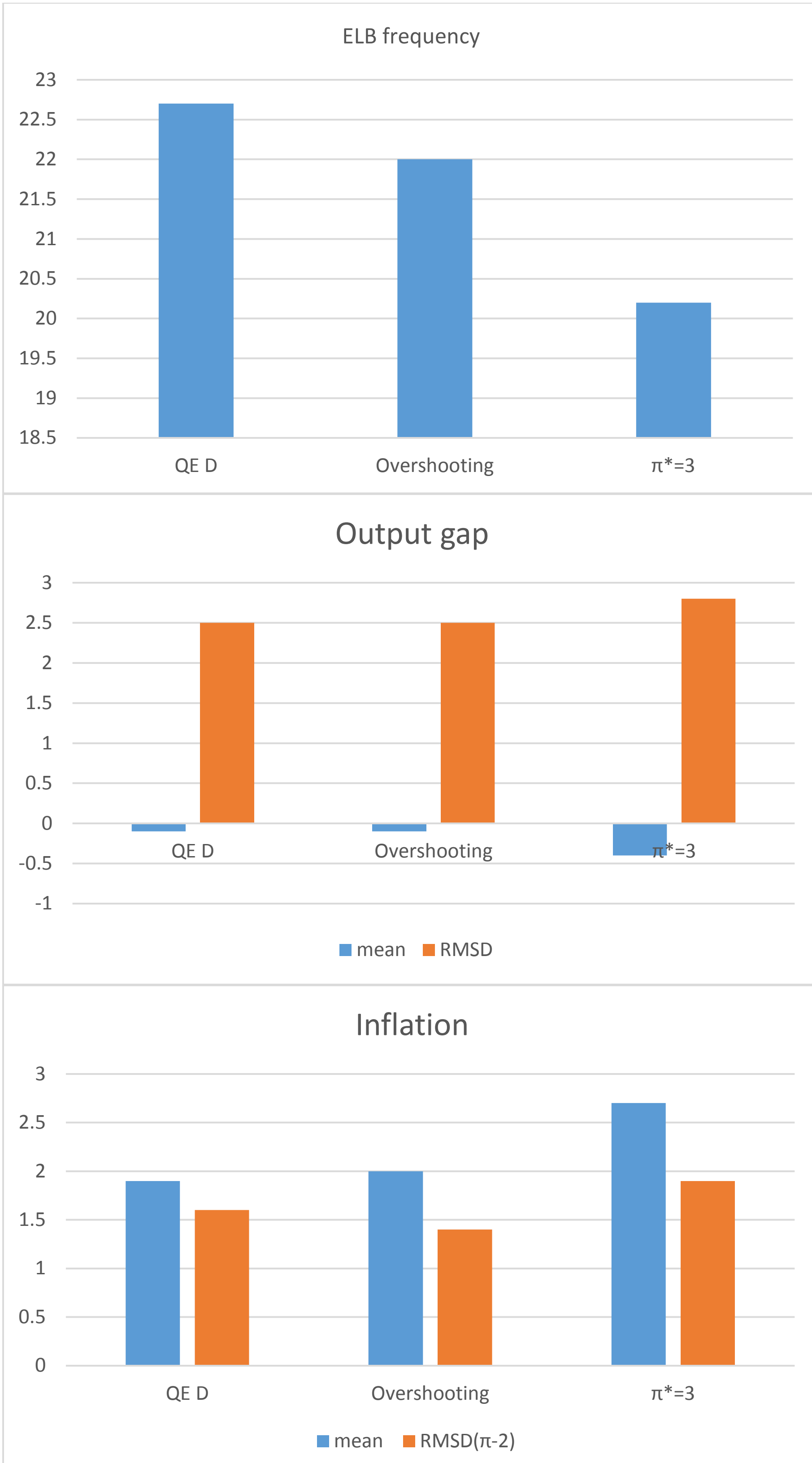
Figure 4 presents outcomes for an equilibrium real interest rate of 1 percent under three strategies: The Taylor (1999) interest rate rule combined with QE D and the commitment approach for inflation targets of 2 percent, and the Taylor (1999) rule with an inflation target of 3 percent; note that the steady-state nominal interest rate in the absent of shocks equals 3 percent under the first two strategies and equals 4 percent under the last strategy. As can be seen in the bottom panels, the commitment strategy is as effective as the aggressive QE strategy (QE D) at stabilizing output and inflation while ensuring that output and inflation equal their objectives, on average, when the steady-state nominal interest rate is as low as 3 percent. In contrast, raising the inflation target while maintaining a policy approach using a simple interest rate rule leads to

[15] It is instructive to walk through the steps delivering the price-level terms. The inflation terms above are $\sum_{i=0}^{3}\pi(t-i) - 2$, which equals $\sum_{i=0}^{3}\big((1-L)p(t-i) - .5\big)$. Multiplying by the inverse of (1-L) yields $\sum_{i=0}^{3}(p(t-i) - .5t)$.

a deterioration in economic performance – output falls short of potential by nearly ½ percent, on average, inflation is higher, and both output and inflation are somewhat more volatile.

As emphasized by Kiley and Roberts (2017), under the change rule that accumulates foregone accommodation in a shadow interest rate, there is hardly any deterioration in macroeconomic performance as the equilibrium real federal funds rate declines. The commitment policies I consider here do not remove accommodation prior to inflation or activity overshooting their desired levels, which may temp policymakers to renege on the strategy. As a result, it is reasonable to question whether this type of commitment could be sustained. Because QE strategies involve contemporaneous actions rather than future actions, the efficacy of these strategies may not have the same credibility problems.

**Figure 4: Outcomes under Alternative Approaches**



## VI. Summary and conclusions

Nominal interest rates may remain substantially below the averages of the last half-century, as central bank's inflation objectives lie below the average level of inflation and estimates of the real interest rate likely to prevail over the long run fall notably short of the average real interest rate experienced over this period. According to simulations of the FRB/US model, monetary policy strategies based on traditional simple policy rules lead to poor economic performance when the equilibrium real interest rate is as low as 1 percent, with the ELB binding nearly 40 percent of the time and both inflation and economic activity falling systematically short of desirable levels.

As a result of these possible adverse conditions, the analysis herein examined systematic approaches to QE as a potential component of the new-normal for monetary policy. Simulations suggest that QE can ameliorate a significant part of the adverse consequences associated with the ELB. Two elements of such systematic approaches are important. First, QE efficacy is enhanced if QE is deployed promptly when output falls below potential, and strategies that delay deployment of QE until output falls quite far below potential are less efficacious. Second, the size of QE responses should be considerable, as such actions were in the United States during the Great Recession. That said, the simulation results do not point to a need for QE efforts to be larger than during the Great Recession: Under the largest program considered herein, the central bank balance sheet rises above baseline by $2 trillion dollars 10 percent of the time, and rises above baseline by more than $3 trillion dollars 5 percent of the time. Moreover, the simulation results suggest that QE can be a secondary tool – used primarily when the short-term nominal interest rate is at its effective lower bound – if it is deployed quickly when a deep recession occurs.

Nonetheless, a few issues remain very important in any contemplation of QE as a standard part of the monetary-policy toolkit. First, the simulation results clearly show that QE is only advantageous if the equilibrium real interest rate is indeed low (e.g., 1 percent or less). While many studies point to this possibility, the econometric evidence is not very strong (e.g., Kiley (2015)). In addition, our analysis has used the FRB/US model, in which the effect of QE on asset prices is calibrated to match outcomes from a small set of event studies. Other event studies and macroeconomic models appear to suggest smaller effects of QE (e.g., Chen, Curdia, and Ferrero (2012), Kiley (2014a, 2014b, and 2016a). As a result, more research on these issues is clearly needed.

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## Appendix: A symmetric QE approach (NOT FOR PUBLICATION)

The simulations in the main text treated QE asymmetrically – the balance sheet responded actively to negative output gaps, but the runoff of the balance sheet was passive (following a simple AR process). As an alternative, simulations were considered in which the balance sheet followed a simple rule, reported in table 6.

In general, economic performance under the posited rule, which brings the balance sheet to $3 trillion when the output gap falls to -7.5 percent, is similar to that under the moderate QE B program presented above. Of note, the symmetric rule responds forcefully to slightly negative output gaps, so the 75$^{th}$ percentile of the QE distribution exceeds $700 billion. Conversely, the rule does not respond as forcefully to tail events as the asymmetric rule (as can be seen by the act that the 95$^{th}$ percentile of the QE distribution under the moderate QE B-asymmetric rule slightly exceeds that for the symmetric rule). This suggests that the willingness to rise the balance sheet substantially for extreme tail outcomes under the aggressive QE D approach outlined above contributes to the very good economic performance under that rule, reinforcing the notion that effective QE must be sizable in some circumstances.

**Table 6: Comparison of QE under Asymmetric and Symmetric Rules**

**For a steady-state nominal interest rate of 3 percent**

| **QE B: Initiation of purchases (AP(t)) when y(t)<-5 at a rate of \$50 billion per quarter per unit of excess output gap** | | | | | | |
|---|---|---|---|---|---|---|
| | ELB frequency | Mean duration of ELB | mean(y) | mean(π) (π*=2) | RMSD(y) | RMSD(π) |
| | 29.8 | 9.2 | -0.5 | 1.6 | 2.9 | 1.8 |
| | Median size | Mean size | 75th percentile | 90th percentile | 95th percentile | |
| | \$1 billion | \$332 billion | \$106 billion | \$947 billion | \$2.09 trillion | |

| **Symmetric QE: QE(t) = (-400 billion)y(t), implying QE=\$3 trillion when y(t)=-7.5** | | | | | | |
|---|---|---|---|---|---|---|
| | ELB frequency | Mean duration of ELB | mean(y) | mean(π) (π*=2) | RMSD(y) | RMSD(π) |
| | 21.0 | 7.1 | -0.6 | 1.6 | 2.7 | 1.9 |
| | Median size | Mean size | 75th percentile | 90th percentile | 95th percentile | |
| | \$120 billion | \$221 billion | \$738 billion | \$1.47 trillion | \$2.07 trillion | |