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THE EFFECTS OF FEDERAL RESERVE'S QUANTITATIVE EASING AND BALANCE SHEET NORMALIZATION POLICIES ON LONG-TERM INTEREST RATES

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Abstract

This paper develops a macro-finance term structure model based on the expectations hypothesis extended to include a time-varying term premium. The model establishes inter alia the link between quantitative easing and the term premium, allowing us to measure the total impact on the bond yield of all phases of the Fed's unconventional monetary policy implementation, including balance sheet expansion and normalization. Furthermore, by focusing on the long-run behavior of the model, an estimate of the equilibrium real interest rate is derived capturing longer-run macroeconomic trends, including the Fed's, pre-financial crisis, balance-sheet trend.

JEL classification: E43, E44, E52, E58

Keywords: Quantitative easing, balance sheet normalization, term structure, time-varying term premium, equilibrium real interest rate

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1. Introduction

The term structure of interest rates has an important place in both macroeconomics and finance. From a finance perspective, it describes the relationship between interest rates with different maturities and the determinants of this relationship. In macroeconomics it is the centerpiece of the monetary policy transmission mechanism. For decades prior to 2008, central banks around the world could affect financial conditions and the real economy by means of setting the level of short-term policy rates; the term structure would then provide the link for these rates to affect long-term interest rates.

However, in the aftermath of the 2008 global financial crisis, as yields at the short end of the yield curve were constrained by the zero lower bound (ZLB), the Federal Reserve and other major central banks had recourse to alternative policy means, beyond conventional interest rate policy, to adjust the monetary policy stance so as to counter the disinflationary pressures induced by the ZLB. Central banks deployed additional policy instruments, such as extensive quantitative easing and enhanced forward guidance, aiming to exert downward pressure on long-term interest rates and reduce the slope of the term structure, and ultimately affect aggregate spending in the economy.

The literature on term structure modeling is vast. A large category of term structure models are affine models that have become very popular in the finance literature of the 2000s. In these models, a number of factors that are sufficient to account for a large part of the variation in bond yields are inferred from the current cross-section of interest rates[1]. Approaches with either yield or latent yield variables as factors have the advantage of providing a close fit to observed yields with a small number of variables; nevertheless they have the drawback that they lack economic interpretation (Gürkaynak and Wright, 2012). Other authors went a step further by using macroeconomic variables as factors in affine models (e.g. Bernanke et al., 2004; Smith and Taylor, 2009) that allowed them to study the response of yields to macroeconomic shocks, albeit at the cost of a poorer fit of the models to the data. Also, macroeconomic and latent variables were combined as factors in this type of term structure models (e.g. Ang and Piazzesi, 2003; Li and Wei, 2013; Bonis et al., 2017; Ihrig et al., 2018). Li and

[1] Most empirical papers use three yield curve factors, which can be interpreted as the level, slope and curvature of yields, e.g., Christensen et al. (2011).

Wei (2013) provide a term structure framework which assumes that yields are driven, through a time-varying term premium, by a small number of factors (state variables), two latent yield factors and a vector of supply variables (a Treasury supply variable and two agency MBS supply variables). The supply variables affect term premia in the same spirit as other macro-variables that are used in macro-finance term structure models. However, to avoid the difficulties in estimating latent factor term structure models, the authors employ two observable yield factors. Also, supply variables are assumed to influence Treasury yields through the term premium channel (Li and Wei, 2013) or their inclusion is motivated by the preferred-habitat term structure model (Bonis et al., 2017; Ihrig et al., 2018)[2]. The use of macroeconomic variables as factors, although economic theory was often invoked to motivate the way factors move, leaves the key component of the model, namely the relationship between yields and factors, rather ad hoc (Gürkaynak and Wright, 2012).

An alternative to the affine term structure models is provided by the expectations hypothesis (EH). According to this hypothesis, changes in the expected path of short-term interest rates are the primary driver of variations in longer-term bond yields, thus suggesting that changes in the slope of the yield curve should systematically relate to subsequent movements in short-term interest rates. The expectations hypothesis in its simplest form allows for a constant term premium over the expected short-term interest rate, which may be maturity-specific but does not change over time.

Earlier approaches to term structure modeling were based on the EH. Nevertheless, a large body of empirical studies have generally found that the data offered little support for this hypothesis (Fama and Bliss, 1987; Campbell and Shiller, 1991). The standard finance explanation for these findings suggests that the term premium may vary substantially over time and that the magnitude of this variation may be a quantitatively important source of fluctuations in the bond market (Cook and Hahn, 1990; Longstaff, 1990). Also, in the context of the EH, a number of studies have considered the possible role of monetary policy in explaining the yield curve (Mankiw and Miron, 1986; Hardouvelis, 1988; McCallum, 1994; Ellingsen and Söderström, 2001; Fendel, 2009) and addressed the linkages between monetary policy and time

[2] The preferred-habitat literature was revitalized in the work of Vayanos and Vila (2009/2021), although Li and Wei (2013) have noted that empirical studies on the preferred-habitat model are practically non-existent, hampered by the lack of detailed data on Treasury holdings across investors and by the complexity of the Vayanos-Vila model.

variation in term premia (Dotsey and Otrok, 1995; Kugler, 2002; Gerlach, 2002). Earlier papers that have accounted for time variation in the term premium, described this premium empirically as an exogenous autoregressive disturbance term (McCallum, 1994), as varying through the dependence of its variance on the variance of the expected change in interest rates (Dotsey and Otrok, 1995), as driven by a single factor correlated to the term spread (Tzavalis and Wickens, 1997; Harris, 2001) or as a serially uncorrelated stochastic term (Ruge-Murcia, 2006). Overall, this literature stresses the need for a more detailed understanding of interest rate behavior and the term premium that takes into account central bank behavior, in an attempt to overcome the empirical weakness of the EH, without requiring however, the abandonment of this theory. More recent efforts to empirically account for the economic forces driving the term premium include variables related to outstanding government debt and the Fed's securities holdings (Kuttner, 2006), business cycle, macroeconomic uncertainty and debt supply variables (Gagnon et al., 2011) or inflation uncertainty (Wright, 2011).

Motivated by changes in monetary policy implementation at the ZLB, this paper takes up a detailed approach to interpreting movements in long-term interest rates, namely the 10-year US Treasury bond yield during the period 1989-2019. Fitting a term structure model to the data represents a reasonable necessary step in order to provide a solid support for the theory underlying such policies as well as to assess their effects. Based on the standard finance model of the EH augmented with time variation in the term premium, we show that the yield curve can be successfully employed to identify the sources of the behavior of long-term interest rates that may be relevant for monetary policy. We find economically significant effects of certain macroeconomic and financial variables on long-term bond yields and, in particular, of short-rate volatility and quantitative easing variables on the term premium.

Our paper contributes to a broad literature on the effects of unconventional monetary policy in a number of ways. First, the use as a starting point of the expectations hypothesis, which is a benchmark model of the term structure of interest rates, allows us to decompose long-term interest rates into expectations of short-term rates and a term premium. We provide a comprehensive analysis of these two components, taking into account the behavior of the central bank also in the light of policy implementation at the ZLB. The EH is augmented with time variation in the term premium since the assumption of a zero or constant risk premium has been recognized as being one of the main reasons for the empirical failure of the EH (Campbell and Shiller, 1991; McCallum, 1994; Dotsey and Otrok, 1995; Rudebusch, 1995). To our knowledge, this paper is the first to use the EH with time variation in the term premium in order to evaluate the effects of unconventional quantitative-easing monetary policy. In this respect, (i) we incorporate a monetary policy interest rate rule in the expectations path of future short-term rates, which effectively provides the link between long-term interest rates and macroeconomic variables (namely inflation, output gap and the equilibrium real interest rate), and (ii) we interpret and estimate the term premium component in terms of two main driving forces: short-rate volatility (suggested in the finance literature) and quantitative-easing monetary policy as reflected in the central bank balance sheet.

Second, the study of the effect of quantitative easing on the term premium has mainly focused on the portfolio rebalancing channel for the transmission of central bank asset purchases to asset prices, according to which central banks could influence the prices of different financial assets considered to be imperfect substitutes, by altering their relative supply in the market. Portfolio rebalancing effects operating via either the local supply (or scarcity) channel around a particular maturity or via a broader duration risk channel across different maturities bring about declines in representative long-term interest rates, such as the 10-year Treasury bond yield, expected to ultimately affect spending in the economy. In addition, a separate signaling channel suggests that large-scale asset purchases by the central bank may also affect expectations for future short-term rates signaling the commitment of the central bank to keep interest rates low for an extended period of time, thus reducing interest rate uncertainty and further compressing yields and the term premium. The theoretical framework adopted allows for both of these mechanisms.

Third, an additional feature of our approach is that it employs alternative aspects of the Fed's balance sheet to measure the quantitative easing policy: on the asset side, the Fed's portfolio of securities and on the liabilities side, the monetary base and bank reserves held with the Fed. These variables estimate the stock effects of the central bank policy (rather than the flow effects) encompassing a rather dynamic view of the central bank balance sheet in that they reflect not only current asset purchases but the evolution of past purchases as well (including the expansion, stabilization or unwinding of asset purchases). Additionally, such measures are not based on balance sheet projections entailing some degree of uncertainty (Ihrig et al., 2018). Our data period is broad enough to cover the whole period after the 2007-2008 financial crisis comprising all phases of the evolution of the Fed's balance sheet: the expansion, the reinvestments-only and the normalization phase. The covered time span provides an advantage compared to other available studies, which focus mostly on earlier or individual phases of unconventional policy implementation (Gagnon et al., 2011; Meaning and Zhu, 2011; D'Amico and King, 2013) or even exclude the crisis period from estimations, providing out-of-sample estimates for the effects of quantitative easing (Gagnon et al., 2011). In particular, we provide estimates of the impact of Fed's asset purchases on the long-term interest rate during the different phases of policy implementation. Furthermore, we distinguish between short-run and long-run effects of changes in the quantitative easing variables on bond yields, providing a deeper insight in the adjustment process of long-term interest rates toward equilibrium. Quantitatively, our baseline estimate, suggests that a one-unit increase in the monetary base-to-GDP ratio should reduce the 10-year bond yield by 53 bps, while in the long run this effect could reach up to around 300 bps. In particular, the Fed's asset purchase programs actually reduced the 10-year US Treasury bond yield by around 70 bps in the balance sheet expansion phase that subsequently unfolded by almost 25 bps in the reinvestment-only and normalization periods up to the end of our sample period in 2019.

Fourth, after documenting the trend-stationarity properties of long-term Treasury bond yields, the inclusion of a time trend in our specification, explicitly recognizes the important role of long-run macroeconomic trends in understanding the dynamics of interest rates and the term premium as well (Bauer and Rudebusch, 2020); such trends could be related to a declining equilibrium real interest rate due to longer-run trends in real factors outside the control of the central bank (such as trends in productivity growth or ageing population). Furthermore, as it has long been recognized that interest rates exhibit a high degree of persistence reflecting long-lived effects of fiscal, monetary, preference or technology shocks, we also account for interest rate persistence in the short-run dynamics of our model.

Fifth, overall the empirical results provide evidence in favor of the proposed theoretical framework. The detailed specification of the long-term interest rate model is reflected in its overall excellent fit to the data over the examined 30-year period. Moreover, the model seems to effectively address two puzzling issues that have been widely discussed in the literature: (i) the bond yield conundrum in 2004-2005, when short- and long-term rates followed diverging patterns and (ii) the bond premium puzzle describing the broader inability of standard theoretical models to generate a sufficiently large and variable term premium. To this end, our macro-finance model of the bond yield, by incorporating the relationship between quantitative easing variables and the term premium, can be seen as an important step allowing us to also account for the above puzzles.

Sixth, a further significant contribution of this paper is that, based on a single-equation specification rather than a broader system of equations, we proceed to deriving an estimate of the equilibrium long-run real interest rate. By focusing on the long-run behavior of our model, we successfully capture the declining trend embedded in the equilibrium real interest rate over the past three decades, brought about by underlying non-monetary real economic trends. An additional innovation of this approach is that our equilibrium real interest rate estimate incorporates the evolution of the central bank balance sheet only to the extent that it is not related to the conduct of quantitative easing monetary policy, but is consistent with its longer-run, pre-crisis trend. According to this estimate, the equilibrium real interest rate stood at 3.8% in 1989, declined to 1.1% before the 2008 financial crisis and fell further to 0.2% at the end of the data period in 2019.

The remainder of the paper is structured as follows. Section 2 provides a thorough overview of the Federal Reserve’s quantitative-easing monetary policy measures adopted in response to the 2008 financial crisis and the ZLB constraint. Section 3 reviews the theoretical and empirical literature on the transmission channels of central bank asset purchases. Section 4 develops our theoretical framework. Section 5 focuses on the empirical analysis and discusses the estimation results, while Section 6 derives the equilibrium long-run real interest rate from the estimated model. Finally, Section 7 summarizes and concludes.

2. The Federal Reserve's unconventional monetary policy measures

Before the global financial crisis, the Federal Reserve used conventional monetary policy tools such as the adjustment of the federal funds target rate to affect overall financial conditions in the economy. It also used open market operations to adjust the supply of reserve balances in the banking system so as to keep the federal funds rate around that target. In response to the financial crisis which erupted in the US subprime mortgage market in mid-2007 and which, after the collapse of Lehmann Brothers in September 2008, evolved into a systemic financial crisis, the Federal Reserve reduced its target rate in decisive steps; at the end of 2008 the target for the federal funds rate had been lowered to a range of 0 to 1/4 percent, which was considered to be its effective lower bound (Figure 1).

[Insert Figure 1 here]

Faced with severe market disruptions, deteriorating economic conditions and persistently weak inflationary pressures and as the federal funds target rate approached its effective lower bound, the Federal Reserve employed a number of unconventional monetary policy measures which have changed markedly the size and the composition of its balance sheet and have attracted a vast amount of public discussion and academic interest.

Initially, in August 2007, the Federal Reserve engaged in reserve-adding repurchase agreements and lowered the rate on its discount window loans. Subsequently, additional credit and lending facilities were introduced to aid the liquidity shortages of financial institutions. These facilities included the Term Auction Facility (TAF), which granted banks ample term loans of central bank funds.[3] At the same time the Federal Reserve entered into agreements with other central banks to establish central bank liquidity swap lines to provide liquidity in US dollars. In 2008, the Federal Reserve offered short-term lending facilities to primary dealers and, later on, to money market mutual funds. In these cases, the Federal Reserve served as a

[3] Under the temporary Term Auction Facility (TAF) program introduced in December 2007, the Federal Reserve would auction term funds to financially sound depository institutions against the wide variety of collateral that were used to secure loans at the discount window. This facility allowed the Federal Reserve to provide term funds to a broader range of counterparties and against a broader range of collateral than open market operations; in this way it could contribute to supporting the efficient allocation of liquidity when the operation of unsecured interbank markets was severely hampered.

lender-of-last-resort to these important classes of financial institutions and with its decisions aimed at restoring market functioning and stabilizing the financial system.

A second group of lending facilities comprised targeted lending programs, such as the Commercial Paper Funding Facility (CPFF) and the Term Asset-Backed Securities Loan Facility (TALF).[4] These programs were intended to provide funding reassurance to financial intermediaries, improve liquidity conditions in the underlying funding markets while facilitating the issuance of commercial paper and ABS, thus contributing to greater availability of credit to businesses and households. As a result of these actions, the asset side of the Federal Reserve balance sheet started to expand and the Open Market Desk allowed some Treasury bills to mature and sold other securities in order to initially sterilize these reserve-adding actions.[5]

However, as the provision of additional monetary accommodation through further lowering the short-term interest rates was no longer considered to be an option, the Federal Reserve started to actively manage the size and the composition of its balance sheet through purchase, sales, and reinvestments of longer-term securities in the System Open Market Account (SOMA)[6] portfolio. Since end-2008 and up to 2014, the Federal Reserve implemented seven different asset programs, summarized in Appendix A and also depicted in Figure 2. In very broad terms, three of them expanded the size of the balance sheet, and four altered its composition, although most of them combined elements of both. Specifically, total assets of the Federal Reserve expanded from $ 1.1 trillion at end-2008 to a peak level of $ 4.5 trillion in the second quarter of 2014.

[Insert Figure 2 here]

The first large-scale asset purchase program (LSAP1), which was announced in November 2008 and further extended in March 2009, involved purchases of certain amounts of agency mortgage-backed securities (MBS), agency debt and longer-term

[4] These programs were introduced at end-2008 and terminated within the first half of 2010.
[5] See Ihrig et al. (2018).
[6] The Federal Reserve System Open Market Account (SOMA) contains dollar-denominated assets acquired through open market operations. These securities serve as collateral for U.S. currency in circulation and other liabilities on the Federal Reserve System's balance sheet, as a tool for the Federal Reserve's management of reserve balances and as a tool for achieving the Federal Reserve's macroeconomic objectives. SOMA holdings are allocated to each of the Reserve Banks on a percentage basis. Transactions for the SOMA are executed by the Federal Reserve Bank of New York. The SOMA also contains the Federal Reserve's foreign currency reserves which are currently held in investments denominated in euros and Japanese yen (Federal Reserve Bank of New York, 2020).

Treasury securities. Since August 2010, the Federal Open Market Committee (FOMC) decided to reinvest principal payments of the Federal Reserve's securities holdings as they matured, so as to keep their level overall constant. At the end of 2010 and in order to promote a stronger economic recovery and ensure that inflation returned at levels consistent with its mandate, the FOMC decided, in parallel with its reinvestment policy, to introduce a second asset purchase program (LSAP2) which would expand the Federal Reserve's holdings of longer-term Treasury securities. In September 2011, reinvestments of principal payments were modified to run from agency debt and agency MBS solely to agency MBS so as to further support the underlying housing market.

Toward the direction of achieving its mandate, the FOMC also adopted a maturity extension program (MEP) in two separate rounds (Sep.2011 and June 2012). In the context of this program, the Federal Reserve sold or redeemed a certain amount of shorter-term Treasury securities and used the proceeds to purchase longer-term Treasury securities, thereby extending the average maturity of Federal Reserve's portfolio of Treasury securities. The purpose was to put further downward pressure on longer-term interest rates relative to short-term ones, without changing the overall size of the Fed's securities portfolio.[7]

In September 2012, the FOMC adopted a third large-scale asset purchase program (LSAP3) for purchasing additional agency MBS at a certain monthly pace, while three months later the program was expanded to include monthly purchases of longer-term Treasury securities. LSAP3 combined with the continuation of the MEP and the reinvestment policy would lower longer-term interest rates, support mortgage markets and help make broader financial conditions in the economy more accommodative.[8,9]

As the economic recovery gained momentum, the FOMC's main interest and discussions turned to issues related to the process of normalization of monetary policy. After slowing their pace since the beginning of 2014, the FOMC concluded net asset purchases in October of the same year, while maintaining the existing policy of reinvestments. This policy would keep Fed's holdings of longer-term securities stable at sizeable levels thus preserving accommodative financial conditions. In September

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[7] Meaning and Zhu (2012).

[8] It should be noted that in contrast to LSAP1 and LSAP2, LSAP3 was announced as an open-ended program without a pre-defined size for the total amount of purchases.

[9] Several papers analyze the transmission channels of asset purchases, which will be discussed in the next section.

2014, it was indicated that the approach of policy normalization would proceed around two main elements: (i) the gradual raising of the target range for the federal funds rate to more normal levels and (ii) the gradual reduction of the Federal Reserve's securities holdings.

In June 2017 the FOMC announced its intention to proceed with a balance sheet normalization program within that year; reinvestments continued at a stable pace up until October 2017. According to the augmented Policy Normalization Principles and Plans in 2017, it was provisioned that the FOMC would reduce the Federal Reserve's securities holdings by gradually decreasing reinvestments of principal payments. Consequently, the policy of balance sheet normalization was expected to result to a declining supply of reserves over time at a level appreciably below that seen in recent years but substantially higher than prior to the financial crisis.

In January 2019, the FOMC outlined its intention to continue to implement monetary policy with an ample supply of reserves in the longer run. Later on, in March, the FOMC described its plans for slowing the pace of reduction of its securities holdings and the associated decline in reserves. However, the Committee noted that when it would judge that reserve balances had declined to a level considered appropriate, the SOMA portfolio would hold no more securities than necessary for an efficient and effective policy implementation. Once that point would be reached, the Committee would begin increasing its securities holdings to keep pace with trend growth of the Federal Reserve's non-reserve liabilities and maintain an appropriate level of reserves in the system. In August 2019, the reduction of the Federal Reserve's securities holdings was concluded. Two months later, in light of recently recorded and expected increases in the Federal Reserve's non-reserve liabilities, the FOMC outlined plans to purchase Treasury bills at least until the second quarter of 2020 and other technical measures in order to maintain an ample supply of reserve balances at or above the level that prevailed in early September 2019.

As a result of the Federal Reserve's various lending facilities and asset purchase programs, the monetary base, and the quantity of excess reserves in particular, rose dramatically on the liabilities' side of the Federal Reserve's balance sheet (Figure 2). While required reserves grew modestly, excess reserves rose from 2 billion $ in the second quarter of 2008 to an unprecedent level of $ 2.7 trillion in the third quarter of

2014 and then gradually decreased to $ 1.3 trillion in the third quarter of 2019.[10] In October 2008, the Federal Reserve began paying interest on excess reserves for the first time in its history.[11] The interest rate on excess reserves (IOER) provided the Federal Reserve an additional tool for the conduct of monetary policy. It was designed to broaden the scope of the Federal Reserve to use its lending and asset programs so as to address conditions in credit markets, while also maintaining the federal funds rate close to the target range established by the FOMC. Furthermore, during monetary policy normalization, the Federal Reserve intended to move the federal funds rate into the target range set by the FOMC primarily by adjusting the IOER rate (Figure 1).[12]

With the aim of enhancing the effectiveness of monetary policy at the zero lower bound, forward guidance also took on a more important role as an additional element of the Federal Reserve's unconventional monetary policy during the crisis. Since end-2008, the Federal Reserve has been providing additional information about the likely future course of monetary policy in its communications with the public, which evolved over time. Thus, the central bank could provide further monetary stimulus to the economy through stabilizing expectations about the evolution of short-term interest rates in the future and containing uncertainty.

3. Overview of the theoretical and empirical literature

As already mentioned, in view of the zero lower bound (ZLB) on interest rates, conventional monetary policy in the form of adjusting policy interest rates, had little room to provide further monetary stimulus to the economy through reducing short-term interest rates.[13] Thus central banks employed unconventional monetary policy tools,

[10] Subsequently, however, excess reserves started to rise again. In the last quarter of 2019, the Federal Reserve engaged in purchases of Treasury bills and offered overnight and term repurchase agreement operations to ensure an ample supply of reserves in light of recent and expected increases in the Federal Reserve's non-reserve liabilities and money market pressures. In the first quarter of 2020, as the coronavirus pandemic shock unfolded, it started to purchase Treasury securities and agency MBS in the amounts needed for an effective transmission of monetary policy to broader financial conditions while it offered new credit and lending facilities to support the flow of credit to the economy.

[11] Keister and McAndrews (2009).

[12] Board of Governors of the Federal Reserve System (2008, 2014).

[13] Banks are reluctant to pass on negative interest rates to depositors, as cash, taken as a zero coupon bond issued by the central bank, can always be held as an alternative to assets which bear a negative interest rate. Since holding cash involves some storage and transportation costs, interest rates can actually go slightly negative thus creating effectively a negative, rather than a zero, lower bound to interest rates (McCallum, 1999 and Cœuré, 2015)

such as large-scale asset purchases or maturity extension programs, focusing on the size and the composition of their balance sheet. The general idea is that these policies affect the term structure of interest rates; they operate directly on different segments of the yield curve reducing rates at longer-term maturities, while short-term rates are constrained by the ZLB. However, in order to evaluate the efficacy of such policies and their contribution to aggregate welfare, the theoretical analysis should provide some transmission mechanism(s) on how such policies may affect asset prices and ultimately, through cost-of-capital or wealth effects, consumption and investment spending.

3.1 Balance sheet mechanics of central bank asset purchases

Unlike conventional policy interest-rate adjustment, large-scale central bank purchases of longer-term government or private sector securities (commonly referred to as quantitative easing) explicitly relate to quantities of assets and are financed by the issuance of central bank money. From a central bank balance sheet perspective, increased central bank assets are matched by increased liabilities in the form of reserves, while during a normalization period when reinvestment of maturing securities is gradually reduced, the central banks' balance sheet contracts correspondingly. Figure 3 shows how the two items of the Federal Reserve's balance sheet, the portfolio of securities which is the major part of its assets and the monetary base on the liability side are closely correlated over the last two decades including the period of unconventional monetary policy.

[Insert Figure 3 here]

Central bank asset purchases from the private sector may come either from banks or non-banks, inducing different changes in the respective balance sheet positions. According to flow of funds data, the bulk of Fed asset purchases came from non-banks (Carpenter et al., 2015). When banks are the sellers of securities, the size of bank balance sheets remains overall unaffected as their securities holdings decrease and their reserves at the central bank increase by the same amount. In case securities are acquired from non-banks, such as households including hedge funds, brokers/dealers or insurance companies, the mechanics are different as these entities cannot directly hold reserves at the central bank. On the asset side of non-banks' balance sheet, holdings of securities decrease and holdings of bank deposits increase by the same amount. At the same time, the corresponding banks' balance sheet is affected: the ensuing increase in bank deposit liabilities to non-banks is matched by an increase in bank reserves at the central bank and, as a result, the banking sector balance sheet expands. Banks and non-banks may take subsequent actions to modify their assets/liabilities. The ultimate effect on their respective balance sheets could work out in many different ways depending on their preferences.

3.2 Transmission channels of central bank asset purchases

The academic literature distinguishes two broad channels for the transmission of central bank asset purchases to asset prices: (i) the signaling channel and (ii) the portfolio rebalancing channel. The signaling channel suggests that a large expansion of the central bank balance sheet may affect investor expectations for the future path of short-term rates to the extent that it reflects information about the state of the economy and the commitment of the central bank to keep policy rates low for an extended period of time. The portfolio rebalancing channel, initially described by Tobin (1969) and Brunner and Meltzer (1973), postulates that central banks could influence different asset prices, through altering the relative supply of financial assets considered to be imperfect substitutes in terms of their duration (or maturity) and liquidity characteristics.

In more detail, the theoretical underpinnings of portfolio rebalancing lie mainly on the local supply (or scarcity) channel and the duration channel of the assets purchased. Under the local supply channel, a reduction in the stock of securities of a particular maturity in the hands of private investors creates a shortage of these assets, thus inducing an increase in their prices and a compression in their yields. Similar adjustments may also be evident in the prices and yields of securities of a similar maturity.

Under the duration channel, investors who are averse to interest rate risk (or duration risk) require a higher expected return for investing in longer-term securities compared to the return required if they invested in securities of a shorter maturity.[14]

[14] Long-term bond yields can be decomposed in two components: the average of expected short-term rates (the "expectations component") and a term premium component reflecting an average of expected excess returns over the lifetime of the bond. Excess returns measure investors expected returns from investing in a bond of a longer maturity, in excess of the risk-free short-term rate prevailing over the life

Central bank purchases of longer-term securities reduce the amount of duration risk to be borne by the private sector, while increasing the short-term risk-free bank reserves in the system. As a result, central bank purchases decrease the market price of duration risk and the expected return (term premium) on purchased securities has to fall relative to the expected return that investors can earn on an alternative roll-over strategy at the risk-free rate for the same term to maturity (Rostagno et al., 2019). Moreover, investors are induced to reallocate the liquidity acquired and their portfolio toward other types of assets. In this way, a large-scale asset purchase program may lead as well to a compression in yields in market segments other than those directly targeted by central bank purchases.

3.3 Central bank asset purchases and imperfect substitution of assets

Monetary policy transmission relies on the effects that monetary impulses may have on prices and yields of financial assets, which in turn affect economic decisions and the real economy. In a traditional IS-LM framework, where there are only two financial assets, money and bonds, all non-monetary assets and debts are considered to be perfect substitutes. When the monetary authorities induce a change in the supply of money, equilibrium is restored by changes in the interest rate for bonds that will ultimately have an effect on real variables. However, in order to allow for an effective transmission of central bank purchases to asset prices, theoretical models needed to depart from such strong underlying assumptions and introduce various types of financial frictions. Such frictions include heterogeneity in asset preferences, asset market segmentation or limits to arbitrage which make different types of financial assets imperfect substitutes.[15]

of the bond. Accordingly, the term premium reflects both the riskiness of long-term bonds and the compensation required by investors for that risk. Abstracting from credit and liquidity risk, the most prevalent source of risk for long-term debt is duration risk, i.e. the sensitivity of the bond price to changes in the term structure of interest rates.

[15] As long as private investors consider different assets as perfect substitutes, central bank interventions should not bring about any effects. At the ZLB, central bank purchases of one-period bonds in exchange for bank reserves, should have no impact on the economy as both of these assets bear no interest and are almost risk-free (Wallace, 1981; Eggertsson and Woodford, 2003); however, the extra central bank money created may signal the central bank's intentions regarding the future path of the short-term interest rate (Krugman, 1998; Eggertsson and Woodford, 2003). This irrelevance proposition for quantitative easing is analogous to the Ricardian Equivalence proposition (Barro, 1974), suggesting that the consumption of the representative agent and the interest rate depend on aggregate government spending and not on the maturity structure of interest rates or on how government spending is financed.

Some authors study the effects of imperfect asset substitution in the context of general equilibrium optimizing-agent models which incorporate some sort of financial frictions. In Andrés et al. (2004) frictions take the form of transaction costs, heterogeneous agents and limited participation which render short- and long-term bonds imperfect substitutes. Consistently with Tobin's view, they consider interest rate differentials as functions of the relative quantities of financial assets in the (unrestricted) household portfolio as captured by the ratio of money to long-term bond holdings. Thus, their model implies that central bank asset purchases may affect long-term rates not only via the expected path of short rates but also through an extra effect on the relative price of alternative financial securities. They estimate that an increase of 1% in money decreases long-term interest rates by about 18 bps, supplementing the traditional expectations channel. Following Andrés et al. (2004) and assuming preferred habitat preferences for assets of different maturities, Chen et al. (2012) simulate the impact of LSAP2 in a DSGE model with bond market segmentation. They assume that a bond risk premium arises in the model as a result of transaction costs (which are considered as a function of the ratio of long-term debt to short-term debt in the hands of the public) and is a positive function of the supply of long-term Treasury securities available to the private sector; however, they estimate a rather low elasticity of the risk premium with respect to the market value of long-term debt and a 11 bps decline in the 10-year Treasury risk premium as the impact of LSAP2, suggesting that these effects would have been even lower without policy commitment to keep interest rates at the lower bound for an extended period of time.

As already informally envisaged by Cullbertson (1957) and Modigliani and Sutch (1966), Vayanos and Vila (2009/2021) and Greenwood and Vayanos (2014) developed and expanded a theoretical term structure model introducing imperfect substitution in terms of preferred habitat preferences on the term structure of interest rates. Shocks to the demand and the supply[16] of bonds affect bond prices and expected returns. In this framework, the maturity structure is determined through the interaction of investors with strong preferences for specific maturities with risk-averse arbitrageurs who absorb shocks and integrate local markets rendering the term structure arbitrage-free. A key prediction of the model is that the supply of long-term bonds (relative to short-term

[16] Specifically, Greenwood and Vayanos (2014) refer to the net supply of bonds defined as the government supply of bonds minus investor demand.

bonds) is positively related to the term spread and long-term bond excess returns, while supply effects are stronger for longer maturities and at times when arbitrageurs are more risk averse. Based on data over the period 1952-2007, Greenwood and Vayanos (2014) estimate that a one standard deviation increase in the supply of government debt (as measured by the ratio of maturity-weighted government debt to GDP) is associated with a 40 bps rise in the 20-year bond yield and a 259 bps increase in its expected return over a one-year horizon. In another version of the Vayanos-Vila model, Hamilton and Wu (2012) also provided empirical support for the effectiveness of central bank asset purchases in influencing the term structure. They suggest that by swapping short-term Treasury securities for longer-term ones at the ZLB, the central bank has the potential to lower longer-term interest rates by 13 bps without raising short-term rates, while the same potential is identified for an outright purchase of $ 400 bn of long-term bonds for newly created reserves. Hayashi (2016) further developed tools for overcoming computational difficulties of the Vayanos-Vila model, providing a discrete-time version of it. He suggested that maturity structure dynamics matter critically for equilibrium bond yields, while the response of bond yields to a local supply shock at a given maturity is evident broadly across all maturities, although more intense around the originating maturity.

In the sense that Bernanke and Reinhart (2004) and Bernanke et al. (2004) explained a portfolio rebalancing effect arising as a result of large increases in the money supply, Christensen and Krogstrup (2019) provide a model in which, apart from supply-induced portfolio balance effects, expansions in central bank reserves that accompany quantitative easing may also lead to portfolio balance effects on asset prices.[17] A necessary requirement for reserve-induced effects is imperfect asset substitutability between central bank reserves, bank deposits and traded securities as well as the segmentation of the market for central bank reserves. As already described, when asset purchases come from non-bank institutions (e.g. money market funds which cannot directly hold central bank reserves), intermediary banks' balance sheets expand, as they passively observe the transactions made by their non-bank customers. They suggest that banks may have a portfolio response to increases in their reserve holdings

[17] Christensen and Krogstrup (2019) argue that the expansion in central bank reserves per se may introduce an additional effect of quantitative easing on long-term interest rates, and provide as evidence the declines in Swiss long-term government bond yields following the announcement of the Swiss National Bank that it would expand central bank reserves by acquiring only short-term securities.

toward long-term assets that may push long-term asset prices up further. The existence of reserve-induced portfolio effects suggests that financial market structure, business models of financial intermediaries and bank regulations may affect the transmission of quantitative easing to long-term interest rates. Furthermore, reserve-induced effects may be more relevant during the period of central bank balance sheet normalization process.

3.4 Empirical issues relating to central bank asset purchases

From an empirical point of view, the two most frequently used approaches for estimating the impact of central bank asset purchases on interest rates comprise high-frequency event studies and time series models of yields/term premia, both of which present their own limitations. Event studies examine changes in bond yields over a very short (few days) window around the announcements of specific policy events. These type of studies are based on certain assumptions such as (i) that policy announcements have been largely unanticipated by market participants and (ii) that these announcements did not reveal information of the central bank about the state of the economy that could otherwise affect bond yields. Overall, these analyses provide evidence of significant financial market responses to the announcement of large-scale asset purchase programs, especially as far as the announcement of LSAP1 and LSAP2 are concerned. They include Swanson (2011), Krishnamurthy and Vissing-Jorgensen (2011), Gagnon et al. (2011), Meaning and Zhu (2011), Wright (2012), Kiley (2014) and Neely (2015). However, many reservations arise regarding event study results. For example, it is often difficult to disentangle the effect of asset purchase announcements from the forward guidance elements, which were also often contained in them. Moreover, event study results may be sensitive to extreme observations while it may also be difficult to measure persistence of effects in an event study framework as it may take some time before changes in the supply of assets are reflected in asset prices or yields (Kuttner, 2018).

Time series analysis has also been employed to study the effects of quantitative easing on bond yields and term premia. This method exhibits several advantages over the event study method. Instead of exploiting a small number of policy announcements, the time series method exploits a broader time path of data enabling more accurate quantitative estimations. An important identifying assumption under this approach is that the variables for the supply of assets of different maturities are considered to be exogenous with respect to the term premium, thus suggesting that neither the Treasury nor the central bank would adjust the supply of assets in response to changes in the term premia. However, endogeneity issues may also arise if both asset supplies and term premia are a function of an omitted variable, such as macroeconomic conditions or financial conditions. This may have been the case during the financial crisis of 2008 when central banks' asset purchases were a response to deteriorating economic conditions. For this reason, many time series studies fit models to the data for the pre-crisis period. One of the drawbacks of this kind of analyses may stem from substantial differences among estimates of term premia across various models, while the assumption of stable parameters in term structure models may be inappropriate during periods of financial crisis.

The stylized time series properties of the term structure of interest rate are often described in the context of affine term structure models,[18] the main advantage of which is their analytical tractability (Piazzesi, 2010). Apart from fitting a term structure model to the data, estimations of the non-directly observable bond term premia are also obtained through these models (Kim and Wright, 2005 and Kim and Orhanides, 2012). Motivated by the preferred habitat term structure model of Vayanos and Vila (2009/2021), Li and Wei (2013) and Bonis et al. (2017) use an affine arbitrage-free term structure model, in which yields are affected by latent yield factors and bond supply variables, suggesting a cumulative decline of 100 bps of the 10-year Treasury term premium due to LSAP and MEP programs.

A representative time-series analysis is Gagnon et al. (2011) who used reduced-form equations to explain the historical variation in the 10-year US Treasury yield and term premium. The authors provide evidence that the Federal Reserve's asset purchases led to significant and long-lasting declines in longer-term interest rates in a broad range of securities. They estimate that a 1% of GDP increase in long-term debt supply increases the 10-year Treasury term premium by 4.4 bps. Similarly, D'Amico et al.

[18] Affine term structure models express bond yields or term premia of different maturities as a function of a small number of state variables, which are assumed to follow a first order vector autoregressive process under the restriction of no arbitrage. The instantaneous short-term interest rate is considered to be a function of the same state variables. All co-movements between bond returns of different maturities are attributed to these variables and only the risk associated with them is priced within the model (Kuttner, 2018 and Bolder, 2001).

(2012) also indicated that the impact of central bank asset purchases on longer-term interest rates was brought about mainly through the term premium component of yields. A one percent reduction in privately held Treasury securities is associated with a 5 bps decrease in the term premium of maturities comparable to those purchased (scarcity effect), while an additional decline of 100 bps is estimated for a one-year decrease in the aggregate duration of Treasury securities held by the private sector (duration effect). Other time series empirical studies providing empirical support for the impact on yields associated with the central bank asset purchases include Williams (2011), D'Amico and King (2013), Meaning and Zhu (2011, 2012) and Ihrig et al. (2012).

4. The theoretical framework

In this section we provide the theoretical framework for our analysis. As we have already discussed, the zero lower bound (ZLB) may be described as a situation in which the central bank has reduced its policy rates at or near zero but slow growth, economic slack and low inflation or even fears of deflation continue to persist. Within such an environment in which short-term interest rates are constrained by the ZLB, unconventional monetary policy may be employed by the central bank to lower long-term interest rates and stimulate aggregate demand. As long as monetary policy affects the term structure of interest rates, i.e. the relationship between interest rates of default-free bonds of different maturities, analyzing the link between central bank behavior at the ZLB and the term structure may provide useful insights in uncovering the macroeconomic forces driving them.

The main channels through which unconventional policies, such as large-scale asset purchases and/or explicit forward guidance, are considered to put downward pressure on longer-term interest rates which will be transmitted to the economy, are (i) through affecting expectations for the future path of short-term rates and/or (ii) through compressing the term premium component of longer-term interest rates and reducing the slope of the yield curve. Under this last aspect, the traditional Expectations Hypothesis (EH) extended to include a time-varying term premium provides a useful framework for analyzing central bank behavior and the way unconventional monetary policy affects long-term interest rates.

According to the EH, the term structure is driven by investors' expectations about future short-term rates. The interest rate of a zero-coupon bond with maturity n at time t should be equal to the average of expected short-term interest rates until the maturity date plus a term premium that may vary with maturity and is constant over time.[19] This equality will be established through arbitrage and will hold for risk-neutral investors. In intermediate cases, corresponding to imperfect substitutability between assets, yields are determined both by expectations of future short-term interest rates and term premia. Thus in a more general framework that allows for the possibility that the term premium is time-varying, the EH may be written as:

$$i_t^n = \frac{1}{n}\sum_{s=0}^{n-1} i_{t+s\,|\,t} + tp_t^n \tag{1}$$

or

$$i_t^n = \frac{1}{n} i_t \; + \frac{1}{n}\sum_{s=1}^{n-1} i_{t+s\,|\,t} + tp_t^n \tag{2}$$

where $i_{t+s\,|\,t}$ stands for the expectation of the short-term interest rate s periods ahead conditional on a time t information set, i_t is the one-period current short-term rate and tp_t^n is the term premium for maturity n which, in our case, is assumed to vary over time. This premium is the component of the long-term rate that accounts for the risk arising from holding a longer-dated bond instead of a sequence of shorter-term ones, compensating investors for potential capital losses arising from the bond's relative exposure to interest rate risk.[20,21]

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[19] Specifically, in its strong version the EH assumes that the term premium is zero, so that the long-term interest rate equals the average of the expected short-term rate until the maturity date. In its weak form, the EH implies a term premium which is maturity-specific but constant over time (Gürkaynak and Wright, 2012). As a result of the EH, one should expect that variations in the slope of the yield curve should be systematically related to subsequent movements in short-term rates. However, several authors have pointed out that, along with deviations from rationality, the existence of time-varying term premia may be one of the reasons for the frequently reported lack of empirical support for the expectations hypothesis (Mankiw and Miron, 1986; Fama and Bliss, 1987; Campbell and Shiller, 1991; Dotsey and Otrok, 1995; Harris, 2001). If the term premium is variable and is omitted from the equation, testing the EH will result in biased and inconsistent estimates (Tzavalis and Wickens, 1997).

[20] In general, the interest rate risk, and thus the resulting term premium, is expected to rise with maturity (Froot, 1989; Longstaff, 1990). It has been found, however, that average term premia tend to flatten out for longer-maturity bonds (Longstaff, 1990).

[21] In the context of consumption-based asset pricing models, the term premium reflects changes in the consumer stochastic discount factor that is used to value the possible state-contingent pay-offs of the bond in the future and is expressed in terms of marginal utility of consumption tomorrow relative to marginal utility of consumption today (Rudebusch, Sack and Swanson, 2007; Rudebusch, 2010). In addition, this premium may be positive or negative depending on the sign of the covariance between the stochastic discount factor and the future shorter-term bond price (Rebonato, 2018; Geiger, 2011).

Once the ZLB has been reached, leaving little room (or no room) to influence long-term rates through further interest rate cuts, the central bank policy aims at stabilizing market expectations regarding future interest rates at very low levels and for an extended period of time. The central bank may influence market expectations through an explicit commitment to maintain short-term rates at the ZLB for a long period of time, which, combined with enhanced central bank credibility, may result in reducing interest rates further out in the yield curve. Moreover, through quantitative easing, the central bank signals its determination to provide abundant liquidity in the financial system until deflationary pressures are effectively eliminated, thus also potentially affecting expectations for short-term interest rates. These policy aspects are consistent with monetary policy affecting the expectations component of long-term interest rates and the EH in its strong or weak form, in the context of which, long-term interest rates change (only) as a result of events or policy actions that alter the current or future course of short-term rates (Gürkaynak and Wright, 2012).

The nominal short-term interest rate is the conventional policy instrument under the direct control of the central bank.[22] From a macroeconomic perspective, the short-term interest rate is determined by macroeconomic variables in the context of a monetary policy reaction function as described by an interest rate feedback rule. We employ a simple forward-looking interest rate rule to describe how the nominal interest rate i_t evolves over time, i.e. how monetary policy is related to macroeconomic conditions. This rule can be derived as a solution to the central bank inter-temporal optimization problem. The central bank's objective function includes two arguments reflecting its main targets of price stability[23] and output stabilization around its potential level:

[22] The central bank conducts monetary policy by setting its policy interest rate target. The overnight money market rate, i.e. the interest rate at which credit and other financial institutions trade reserve funds with each other overnight (the federal funds rate), although essentially determined by the market, is influenced by the central bank through open market operations so as to reach the policy rate target. Other short-term interest rates such as the rate of return paid to holders of US Treasury bills or commercial paper issued by private companies are affected by changes in the level of the federal funds rate while changes in short-term market interest rates as a result of changes in the federal funds target rate are also typically transmitted to medium- and long-term interest rates such as those on Treasury and corporate bonds.

[23] We implicitly assume that the long-run inflation target is zero (see also Clarida et al. 1999). In cases that the long-run inflation target is considered to be different from zero, the respective argument in the loss function appears as $\pi_t - \pi^*$, i.e. as the deviation of current inflation from the long-run inflation target (e.g. Svensson, 1997 and 2003). Then, the inflation target π^* will appear in the reaction function of the central bank in the constant term in addition to the natural real rate of interest.

$$L_t = \frac{1}{2} E_t \sum_{j=0}^{\infty} \beta^j [\, \pi_t^2 + \varphi x_t^2] \tag{3}$$

where π_t and x_t are the inflation rate and the output gap in period t respectively, E_t denotes expectations conditional upon information available at time t and β is the discount factor, with $0 < \beta < 1$. The parameter φ reflects the relative weight of the output gap and is expected to range from 0 to 1 and to be closer to 0 when price stability is the main objective of the central bank. The problem of the central bank entails the choice of a time path for the short-term rate i_t, so as to obtain a time path for π_t and x_t that minimizes its loss function. The central bank aims at minimizing L_t subject to two constraints, a forward-looking aggregate demand equation and a forward-looking aggregate supply equation of the New-Keynesian type:

$$x_t = b_0 - b_1 \left(i_t - \pi_{t+1\,|\,t}\right) + x_{t+1\,|\,t} + e_{yt} \tag{4}$$

$$\pi_t = \beta \pi_{t+1\,|\,t} + a_1 x_t + e_{pt} \tag{5}$$

where $\pi_{t+1\,|\,t}$ and $x_{t+1\,|\,t}$ are the expectations of period t+1 inflation rate and output gap respectively, conditional on a time t information set, $b_0 = b_1 \rho$ and $\rho = -ln(\beta)$, ρ is the (exogenous) natural real rate of interest,[24] b_1 measures the response of the output gap to the real interest rate with $b_1 > 0$, α_1 is the sensitivity of inflation to output gap changes with $\alpha_1 > 0$, and e_{yt} and e_{pt} are a preference shock (demand shock) and a cost-push shock (supply shock), respectively.

The optimal rule derived as a solution to the inter-temporal optimization problem of the central bank takes the following form and its derivation is analytically presented in Appendix B:[25]

$$i_t = \frac{b_0}{b_1} + \frac{1}{b_1} x_{t+1\,|\,t} + \left(1 + \frac{\beta a_1}{b_1(\varphi + {a_1}^2)}\right) \pi_{t+1\,|\,t} - \frac{a_1}{\varphi + {a_1}^2} e_{pt} + \frac{1}{b_1} e_{yt} \tag{6}$$

[24] This rate corresponds to the short-term real interest rate which, in the long run, is consistent with aggregate production at potential and price stability (Kiley, 2020).
[25] A similar derivation is also provided in Brissimis and Magginas (2017).

The terms $\left(1+\frac{\beta a_1}{b_1(\varphi+a_1{}^2)}\right)>1$ and $\frac{1}{b_1}>0$ in the above rule measure the strength of the interest-rate response to variations in expected inflation and in expected output gap. The feedback coefficient of expected inflation exceeds unity, implying that the central bank adjusts (raises or lowers) the policy rate sufficiently enough to offset inflationary or deflationary pressures (Taylor principle, Taylor (1993)). With a zero (expected) inflation and output gap, the central bank has to adjust the nominal interest rate so that it reflects movements in the natural real rate (Galí and Gertler, 2007).

The EH could then be used to provide, through investors' expected changes in interest rates, a link between the long-term interest rate and the state of the economy. The respective relationship obtained by replacing the monetary policy rule in the expectations component of the EH is analytically presented in Appendix C and is given by:

$$i_t^n = \frac{b_0}{b_1} + \frac{1}{n}\left(1 + \frac{A}{b_1}\left(1 - \frac{1}{B}\right)\right)(1 + Z^n)\left(\left(\frac{1}{\beta}\pi_t - \frac{a_1}{\beta}x_t\right)\right) + tp_t^n \tag{7}$$

with $A = \frac{\beta\, \alpha_1}{(\varphi+a_1{}^2)} > 0$, $Z^n = 1 - \frac{B}{B^{n-1}} > 0$ and $B = \beta - \alpha_1 A > 0$.

Overall, our analysis of the expectations component of the long-term interest rate suggests that this rate is ultimately a function of current economic developments in inflation and output gap, as it is assumed that investors modify their expectations of inflation as current inflation π_t and output gap x_t change.

As far as the term premium component is concerned, a large part of empirical work has suggested that the EH has not been compatible with the data and this has often been attributed to variations of the term premium over time. The conditions posed by the ZLB provide additional reasons for attempting to reconcile the EH theory with time-variation in the term premium: as the central bank's power to influence long-term interest rates through further reductions in short-term rates is drastically limited, changes in long-term rates should be mostly accounted for by changes in term premia. In addition to monetary policy responses to movements in inflation and the output gap, the incorporation in the term structure equation of a time-varying term premium may enrich its information content. In this context and with a view to providing a more comprehensive representation of the term premium, we consider a number of determinants of the premium, the importance of which may change over time.

According to standard theoretical models of the term structure, the term premium should depend on interest-rate (short-rate) volatility (Cook and Hahn, 1990; Longstaff, 1990; Kugler, 2002; Adrian, Crump and Moench, 2013) which reflects the level of uncertainty about monetary policy or, more broadly, about future movements in interest rates. The rationale behind this argument is that as long as the term premium is seen as a compensation for potential capital losses stemming from future interest rate movements, an increase in interest rate volatility should increase the respective premium demanded by investors (Hicks, 1946; Cook and Hahn, 1990).[26] It should be expected that the longer the maturity of a bond, the higher its exposure to interest rate volatility.

Monetary policy behavior at the ZLB should also be taken into account for a more detailed understanding of the factors determining the term premium. As we have already discussed, at the ZLB the central bank cannot provide further stimulus to the economy by lowering its policy rates and it may have recourse to unconventional policy instruments, such as large-scale asset purchases, to stimulate economic activity. These purchases may affect the term premium and thus longer-term interest rates through the signaling and/or the portfolio rebalancing channel. Through the portfolio rebalancing channel, quantitative easing can bring about a reduction in long-term rates in addition to that implied by the expected path of short-term interest rates.

Under the assumption of perfect substitutability between assets, monetary policy can operate only through affecting the expected path of interest rates. However, under imperfect substitutability between assets, due to financial frictions, portfolio adjustment costs and/or heterogeneous preferences of market agents, quantitative easing decreases the relative supply of financial assets available to the private sector, giving rise to an increase in their price and compressing the term premium component of their yields.

[26] The term premium is assumed to comprise two parts: a real risk premium which is seen as the compensation required for bearing risks stemming from variable future short-term real interest rates as well as an inflation risk premium which is regarded as the respective compensation required against uncertain future inflation developments (Kim and Wright, 2005; Cohen et al. 2018). Considerable changes in the level of macroeconomic volatility, along with perceptions that these conditions will persist, may induce investors to require a different term premium.

This is so because, by reducing the stock of the purchased securities available to the private sector, the central bank induces investors to reallocate their portfolios towards alternative securities. The extent to which such reallocation will materialize should depend on investors' preferences, the degree of market segmentation and investor risk aversion as well as the sensitivity of market participants' demand for the purchased assets to asset price changes. Thus, the effects of QE on the term premia could be either more local, i.e. related to maturities around those purchased by the central bank or more broad-based across different maturities.

Indeed, in outlining the effect of QE on term premia and bond yields, some economists appeal to the preferred habitat theory (see e.g., Kohn, 2009) which works its way through a local supply or scarcity channel, a mechanism under which the purchase by the Federal Reserve of bonds of a particular maturity extracts assets from investors who are particularly interested in that maturity and leads to lower yields of those bonds, while not affecting securities with maturities distinctly different from those of the bonds purchased (D'Amico et al., 2012)[27]. Others (e.g., Gagnon et al., 2011) opt for an alternative channel of portfolio rebalancing, namely the duration channel under which the Federal Reserve purchases decrease the overall duration risk to be borne by the market, thus compressing term premia and yields on securities across all maturities and not only at (or near) the maturities of the bonds acquired. In any case, the distinction between the local supply (scarcity) channel and the duration channel of unconventional monetary policy transmission could not be of much help when individual bond maturities are analyzed[28]. Furthermore, it is the combined downward effect of central bank asset purchases through both local-supply and duration channels on the representative longer-term interest rate that matters for aggregate demand and economic activity.

By using the determinants of the term premium discussed above, equation (7) becomes:

[27] As already mentioned, a recent variant of this approach was developed by Vayanos and Vila (2009/2021).

[28] Harris (2001) noted that all of the studies that examined the expectations hypothesis considered its implications for individual bond maturities in isolation; he suggested alternatively that a number of bond maturities should be combined allowing also for a time-varying term premium.

$$i_t^n = c_0 + \underset{(+)}{c_1 \pi_t} + \underset{(-)}{c_2 x_t} + \underset{(+)}{c_3 unc_t} + \underset{(-)}{c_4 qe_t} + u_t \tag{8}$$

where unc_t is interest rate uncertainty, qe_t is a quantitative easing variable and u_t is an error term. In particular, we should expect π_t and unc_t to be positively related to the long-term interest rate, while x_t and qe_t should be negatively related to it. In the following section we are going to estimate this equation.

5. Empirical analysis

5.1 Model, variables and data

We now provide an empirical assessment of the long-term interest rate equation derived in the previous section (eq. 8) and examine its ability to track the course of long-term rates in the US economy during the period 1988-2019 (Figure 4A). As it has already been analyzed, we use as a starting point a simple term structure equation as represented by the Expectations Hypothesis augmented with a time-varying term premium, which has played an important role in finance and monetary theory. Specifically, we consider a macroeconomic perspective on the expectations component of the long-term interest rate, which in effect links it to the current state of the economy (namely current inflation, output gap and the equilibrium real interest rate) through a short-term interest rate rule. In addition, we further elaborate on the term premium component, an unobservable component of yields in standard finance theory. We account for time variation in the term premium by encompassing the impact of two factors, i.e. interest rate volatility and unconventional quantitative-easing monetary policy. Within this framework, which exploits the interactions between macroeconomics and finance, we are able to better understand how conventional and unconventional monetary policy may affect interest rates and asset prices through various channels of transmission that could work either through the expected path of short-term interest rates or through the term premium. To study these interactions empirically, we rely on the estimation of equation (8), which we repeat here for the sake of convenience:

$$i_t = c_0 + c_1 \pi_t + c_2 x_t + c_3 unc_t + c_4 qe_t + u_t \tag{9}$$

where i_t denotes the long-term government bond yield, π_t is the inflation rate in terms of the GDP deflator, x_t is the output gap, unc_t is a bond market volatility index and qe_t stands for a measure of unconventional quantitative easing. In addition, c_0 is a constant, which, according to the preceding theoretical discussion, represents the equilibrium (natural) real interest rate.[29]

[Insert Figure 4 here]

Inflation is one of the main factors that contribute to explaining the path followed by long-term interest rates. Bond yields should be higher during periods of high inflation as this reduces the purchasing power of the money with which bond investors expect to be repaid. After the successful disinflationary effort of the Fed in the early 1980s, inflation in the US has gradually moved downward and, over the past two decades, is broadly consistent with the Federal Reserve's inflation mandate (Figure 4B). These developments can be attributed to the credibility of the Fed for achieving price stability which has contributed to stabilizing long-run inflation expectations around the Fed's inflation target over time. In this way, by ensuring that inflation would remain well under control, the Fed had more flexibility in the short run to react to shocks affecting output and employment. However, a persistently low level of inflation in the context of the ZLB of interest rates may also suggest that the risk for bonds arising from high inflation remained rather contained in recent years.

The output gap is the second variable of interest to the central bank which is factored into monetary policy decisions. It is generally regarded as an indicator of the degree of utilization of the economy's productive capacity, mainly reflecting short-term variations in demand. In principle, the output gap is conceptually appealing for monetary policy as it may be an important driver of short-run inflationary pressures. A positive output gap, i.e. when real output is above potential, indicates a high utilization of capacity in times of strong demand; in this case, the more actual output exceeds potential, the stronger the upward pressure on factor costs and inflation in the short run will be. On the contrary, a negative output gap, i.e. when real output is below potential, implies slack in the economy, so that downward pressures on factor costs and inflation

[29] The natural real rate of interest can be defined as the real rate which is consistent with real GDP at its potential level and is not related to monetary factors. Potential output is the level of output that the economy would produce if productive resources were employed at maximum sustainable rates, i.e. rates that are consistent with steady growth and no pressure for prices to rise or fall (Williams, 2003).

may start to take hold. Figure 4C shows that, during economic downturns, the US economy operated at a lower level than its potential for several years as the output gap was predominantly on the negative side. In particular, during the deep recession that followed the financial crisis of 2007-2008, the output gap fell more strongly than on average in previous cycles, reaching a minimum in 2009, and since then it gradually closed, turning positive again at the end of 2017. This was associated with the fact that real output increased only slowly after the recession trough in 2009, counter to normal expectations of a rapid cyclical recovery.[30] The slow post-crisis recovery may for one reflect the ZLB that significantly restricted the scope of monetary policy during the recovery, while unconventional monetary policy tools may be associated with a slow adjustment of longer-term interest rates. The consequences of the financial and economic disruption caused by the crisis, perhaps reinforced by post-2008 regulatory changes could also have played a role in the slow recovery (Eberly et al., 2019). In addition, the weak recovery of output took place on the back of a slowing trend in potential output that had begun already before the crisis, since the early 2000s. The main drivers behind this trend slowdown have been slow productivity growth and a declining labor force participation rate (Fernald et al., 2017 and 2018). Structural changes may also have altered the balance between savings and investment that brought about a decline in the equilibrium real rate of interest, complicating the conduct of monetary policy at the ZLB (Summers, 2014).

In our specification of the bond yield equation, we allow the output gap variable to also affect the bond yield with a lag. Lagged output gap recognizes that successive observations of the components of this series (real output, potential output) exhibit a high temporal correlation (Gerlach and Smets, 1999; Rudebusch, 2010).

Turning to the term premium component of yields, interest rate uncertainty has since a long time been recognized as a fundamental factor explaining it. Increased uncertainty about the near-term outlook of the economy or the course of monetary policy may suggest increased risks for bond investors arising from unexpected movements in interest rates that could result in capital gains or losses. With the exception of the period 2007-2008, bond market volatility seems to have been on a declining path since the early 2000s, as depicted in Figure 4D. This decline could be

[30] For potential explanations on the issue of recessions being followed by a stable or increasing output gap, see Blanchard et al. (2015).

partly related to the increased emphasis placed by the FOMC in the last two decades in communicating openly and clearly its policy intentions and outlook. The Fed's communication, which has evolved gradually since 1999,[31] is considered to have contained risks and volatility in financial markets while allowing for a smooth adjustment of the economy to policy changes. Furthermore, to the extent that central bank communication provides guidance about the likely future path of short-term interest rates, monetary policy is able to affect the economically relevant longer-term interest rates more effectively (Bernanke, 2013). At the ZLB, enhanced forward guidance and expectations that short-term rates will remain low for an extended period of time may have also contributed to the decline in the volatility of yields. We proxy bond market volatility using the MOVE index, an option-based implied volatility index[32] constructed by Merrill Lynch, which has been found to co-move closely with estimations of the bond term premium; this observation suggests that the expected volatility extracted from Treasury securities options reflects, at least to some extent, movements in the required compensation demanded by investors against unexpected movements in interest rates, and most prominently the risk of unexpected inflation (Bernanke, 2015; Abrahams et al., 2015).

The second factor, which in the context of our joint framework explicitly relates to the term premium, is the quantitative easing policy of the central bank in terms of its balance sheet expansion through large-scale asset purchases. By employing quantitative easing since December 2008, the Fed tried to directly affect long-term interest rates to support the economic recovery at the ZLB and the return of inflation over time to levels consistent with its mandate. As already described, this policy involves both the asset side and the liabilities side of the Fed's balance sheet, as the central bank increases its longer-term securities holdings in exchange for reserves held by banks. Furthermore, the pace of the reinvestment policy of maturing securities allows the Fed to either maintain or reduce the size of its balance sheet. In particular, large-scale asset purchases reduce the supply of long-term securities available to the private sector, while at the same time they are associated with an increase in the supply of bank reserves with zero

[31] The FOMC started to release statements after its meetings, in May 1999 (Bernanke, 2004; Wynne, 2013).

[32] The Merrill Lynch Option Volatility Expectations (MOVE) index is a weighted index of implied volatilities on 1-month Treasury options at different maturities which are weighted on the 2, 5, 10 and 30- year contracts.

duration. The reduction in the supply of the longer-term assets will reduce the yields of these assets by reducing the term premium required to hold them, bringing about portfolio rebalancing on the part of investors seeking to re-invest the money they hold, and will stimulate economic activity through channels similar to those of conventional monetary policy (Bernanke, 2012). The adjustment of the portfolios of investors/savers and of firms' financing decisions will continue up to the point where banks in aggregate are willing to hold the overall supply of reserves.

To estimate the effect of the Fed's balance sheet policies on the long-term interest rate, we employ three alternative variables, all scaled by GDP : (i) the monetary base, comprising currency in circulation and reserves of depository institutions at the Fed, as a proxy of the size of the Fed balance sheet, (ii) total securities held outright by the Fed, comprising agency debt, agency mortgage-backed securities and Treasury securities, which are the largest category of assets in the Fed's balance sheet, and (iii) bank reserves, both required[33] and excess reserves, held at the Fed, which are the largest part of the Fed's liabilities. Figure 4E presents the path followed by the three alternative balance sheet variables. All three variables recorded a sharp rise in their level since end-2008 after the introduction of the Fed's credit and quantitative easing measures, while they all showed a gradual decrease since 2014 after the start of the Fed's balance sheet normalization. After the start of the quantitative easing operations, the monetary base was exceeding the Fed's securities holdings up to 2010 but since mid-2012 it fell slightly below[34]; in any case, both these variables as well as the reserves variable exhibited similar fluctuations during the post-crisis period.

[Insert Table 1 here]

Table 1 provides more details for the exact definition of the variables used in the empirical analysis, while Table 2 provides the respective descriptive statistics. We estimate the long-term interest rate equation using quarterly data for the period 1988Q4-2019Q3.[35] The source for most of the data is the Board of Governors of the Federal Reserve System; the data are retrieved from FRED, Federal Reserve Bank of St. Louis.

[33] The reserve requirement ratio was reduced to 0% since end-March 2020, eliminating reserve requirements for all depository institutions.
[34] Several factors such as substantial reductions in the recourse to the Fed's liquidity and credit facilities and, later on, the increase in factors absorbing reserve funds such as reverse repurchase agreements, seem to have contributed to sustaining a level of securities holdings above the monetary base.
[35] 1988Q4 is the earliest quarter for which there was data availability on the bond market volatility index as provided in Thomson Reuters Datastream.

With the exception of the bond yield, the bond market volatility index and the Fed's securities holdings, all variables are constructed based on seasonally adjusted data, while all variables, except for the bond yield and the bond market volatility index, are expressed in logarithmic form.

[Insert Table 2 here]

Before turning to estimation, the stationarity properties of the data need to be assessed. Table 3A reports the Augmented Dickey-Fuller (ADF) statistic testing the null hypothesis of the presence of a unit root in the variables of our model versus three alternative hypotheses: the variables are (a) stationary, (b) stationary around a constant and (c) stationary around a constant and a linear time trend (trend stationary). Table 3B reports the ADF test results for the variable(s) for which a breakpoint is identified – the quantitative easing variable(s). The results in Table 3A indicate that the bond rate is a strongly trend stationary variable consistently with its diagrammatic representation showing a downward trend for the most part of the period under examination. Also, the ADF test provides strong evidence that the inflation rate may be a stationary variable with a non-zero mean and a trend. Thus, the inflation rate moved downward during the disinflation period of the 1980s but thereafter has remained rather stable on average, broadly in line with the Fed's inflation objective. A similar picture arises for the interest rate uncertainty variable, which remained rather stable until early 2000s and then – with the exception of the spike of 2009-2010 – stands at a very low level. The results of the unit root tests suggest that this variable may also be stationary with a non-zero mean and a trend. The output gap variable has remained for some time periods below zero and others above it, while the unit root test results provide some evidence that the variable may be stationary with a zero mean.

As far as the alternative quantitative easing variables are concerned, initial tests show that we cannot reject the null hypothesis for the existence of a unit root (Table 3A). However, due to the fact that these stock variables increased dramatically at end-2008 relative to the state prior to the financial crisis (see Figure 4E) and that conventional unit root tests are biased toward a false unit root null when the data are trend-stationary with a structural break, we repeated the ADF test accounting for a breakpoint in these variables. The modified ADF test that we used allows for levels and trends that may differ across a single break date. The test may be computed with a structural break, where the break consists of a level shift, a trend break or both a shift and a trend break. Our results are presented in Table 3B. From these results it appears that if we take into account the respective break in the variables during the year 2008, all three alternative measures of quantitative easing turn out to be stationary around a constant and/or a trend.

[Insert Table 3 here]

Consistently with the results of unit root tests indicating that the long-term interest rate variable and other explanatory variables are trending series, a linear trend has been included in the bond yield equation with the aim of placing emphasis on the role of macroeconomic trends in the determination of interest rates and, in particular, of the declining trend in the equilibrium real interest rate which has been recorded over the greatest part of the period under examination. Several analyses of the US economy suggest that the equilibrium real interest rate has moved significantly downward over the past two decades (Williams, 2003, Summers, 2014) with a particularly sharp drop during the financial crisis of 2007-2009 and a mere stabilization around very low levels in the last few years of the period under review. These estimates imply that the natural rate may not be constant over time but may exhibit time variation due to structural changes affecting aggregate supply and/or demand over time (such as demographic and labour market trends, variations in investment or technological innovations).

We also allow for the possibility that interest rates are highly persistent[36] and that bond yields adjust only gradually to the level suggested by the macroeconomic and financial variables in our specification. The dynamics of i_t may arise due to a variety of shocks such as fiscal, monetary, preference or technology shocks, the effects of which can persist for a very long time. Thus, eq. (9) takes the following form:

$$i_t \;=\; c_0 + c_1\pi_t + c_2x_t + c_2'x_{t-1} + c_3unc_t + c_4qe_{i,t} + \; c_5i_{t-1} + \; c_6t + u_t \qquad i = 1, 2, 3 \qquad (10)$$

with u_t standing for an error term capturing macroeconomic or monetary policy shocks and t is a time trend.

5.2 Estimation method and empirical results

Based on the results of the unit root tests, there is a strong presumption that our time series are stationary. Specifically, the evidence suggests that the output gap series

[36] Bauer and Rudebusch (2020), Nelson and Plosser (1982), King et al. (1991) and Caporale et al. (2022).

is a stationary process with a zero mean, the long-term rate, inflation and uncertainty are stationary processes around a constant and a trend, while the quantitative easing series appear to be trend stationary processes with a level shift. The mean reverting behavior in our time series data enables us to initially appeal to the classical linear regression analysis to obtain unbiased coefficient estimates using OLS. A time trend has been included in our specification to allow for unobserved trending factors that may affect the long-term interest rate and the explanatory variables. The time trend interacts with a dummy variable for the period prior to 2012q2 (1989q1-2012q2) to account for a differential slope coefficient of the long-term interest rate between these two periods (as is also evident in Figure 4A). The errors are assumed to be independently and identically distributed following the normal distribution. We argue that the specification of equation (10) presents complete dynamics so that no further lags of any variable need to be included and the error term is serially uncorrelated.[37] We also use robust standard errors to account for heteroscedasticity in the error term that might render the usual OLS standard errors and statistics inappropriate. We additionally estimate equation (10) by using GMM in order to ensure the robustness of our results and obtain consistent (free of simultaneity bias) coefficient estimates.

After the initial estimations providing the short-run effects, the coefficients of the long-run equation were derived. Long-run coefficients have been calculated by dividing the estimated short-run coefficients with the speed of adjustment parameter and were in turn used for arriving at an estimate of the equilibrium real interest rate presented later in section 6.

The results of OLS estimation are presented in columns (1)-(3) of Table 4. The three alternative columns differ with respect to the definition of the unconventional monetary policy variable employed each time, representing a different aspect of the central bank balance sheet (monetary base-, Fed' securities portfolio- or reserves- to GDP ratio, respectively). The results of the Arellano-Bond tests of 1st to 3rd order autocorrelation verify that there is no autocorrelation in the error term. Overall, all estimated coefficients have the expected sign, are statistically significant, take plausible values and are broadly consistent across estimations with either measure of the quantitative easing variable.

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[37] See Wooldridge (2013).

[Insert Table 4 here]

The specification of equation (10) allows for the short-run dynamics of the long-term interest rate, describing an adjustment process that is distributed over time. This is in line with the broadly held view in the literature that the degree of persistence in interest rates is high (Caporale et al., 2022; Neely and Rapach, 2008). Theoretical models suggest that potential causes for interest rate persistence may be fiscal, monetary, preference or technology shocks. The effects of such shocks on interest rates seem to be long-lived; however, interest rates are expected to ultimately revert to their mean.

The coefficient of the lagged interest rate (which stands for 1-δ, where δ is the speed of adjustment coefficient) is highly significant taking values between 0.82 and 0.87 that indicate a rather slow speed of adjustment of the interest rate to the level suggested by the macroeconomic and financial variables in the model. The resulting adjustment coefficient shows that in a given quarter the long-term interest rate adjusts by one-fifth to one-eight of its deviation from equilibrium. The estimated adjustment process appears to be somewhat faster under the monetary base and the Fed's securities holdings measures of the central bank balance sheet for quantitative easing compared to the case of the bank reserves measure.

Within the framework discussed earlier, the long-term interest rate is linked, from a macroeconomic point of view, that relates to the expected path of short-term rates, to inflation, the output gap and the equilibrium real interest rate. From a financial perspective, which relates to the term premium, the long-term interest rate is linked to interest rate volatility and unconventional quantitative-easing monetary policy.

Estimation results verify that among the macroeconomic factors, inflation is significant in explaining long-term rates and, as expected, the respective coefficient is positive. A one percent increase in the GDP deflator should increase the long-term interest rate by about 10 basis points. After the Volcker's disinflation period, price stability conditions had broadly been met during the 1990s as a result of the Fed's credible inflation targeting policy; thus the level of long-term bond yields should have largely reflected over time the decline in inflation and ensuing anchoring of inflation and inflation expectations.

The output gap, which is the second contributor to the expectations component of yields, is also found to be consistently and highly significant. As already discussed, we allowed for the fact that the output gap may also exert a lagged effect on the long-term rate by including in estimation, apart from current output gap, one lag of this variable. Results verify this intuition as both current and lagged output gap are highly significant and take the opposite sign. Overall, the cumulative effect of the output gap is negative at almost 2 basis points. This negative impact could be attributed to the fact that for the most part of the data period 1989-2019, the output gap has been on the negative side, suggesting that for long time intervals output remained below potential, and that subsequent economic slack and subdued inflationary pressures may have resulted in an overall downward impact on yields.

The constant term, which is a component of the equilibrium real interest rate, is found to be negative ranging between -0.9% and -0.5% across the three alternative estimations. The negative level of this rate is consistent with the decline in the natural rate over the past two decades recorded in many studies (e.g., Holston et al., 2017), having reached historically low levels in the most recent years as a result of the 2008 financial crisis and the experience with the ZLB. The inclusion of the interacted time trend also delivers a negative and highly significant coefficient, verifying a declining trend in the equilibrium real interest rate for the most part of the period under examination reflecting, as described earlier, longer-run trends in fundamental real factors outside the control of the central bank such as trends in productivity growth.

As for the financial factors accounting for variations in the term premium, interest rate uncertainty is found to have a positive and significant effect, but rather low in magnitude, as the respective coefficient ranges between 0.3 and 0.4 basis points. It should be noted that in the empirical specification of equation (10), this variable was best proxied by using the first lag of the Move index measure for bond market volatility. The decline in inflation volatility attained through credible inflation-targeting monetary policy of the Fed, improved central bank communication with the public to influence market expectations about future short-term interest rates and, in particular, enhanced forward guidance on the evolution of future short-term interest rates during the ZLB, may have been important in lowering interest rate uncertainty and thus compressing the term premium. For example, between the last quarter of 2013, when the Fed changed its forward guidance for the federal funds rate remaining at the ZLB, from "at least until" to "well past" the QE-end date, and the first quarter of 2014, when this reference was removed, our estimations imply a simultaneous decline of around 20 basis points of the bond yield brought about by a decline in interest rate uncertainty. It should be noted though that this factor loses some statistical significance in column (2) with the Fed's securities portfolio-to-GDP ratio used as the qe variable, probably because forward guidance on interest rates often coincided with the evolution of LSAPs.

In addition, the unconventional quantitative easing of the Fed is estimated to have brought about a substantial negative effect on bond yields. The respective coefficients are highly significant ranging between -0.53 and -0.43 for the regressions using the monetary base- and the Fed's securities-to-GDP ratio, while a weaker effect of -0.15 and of somewhat lower significance is estimated in the case of the reserves-to-GDP ratio. A one unit increase in the relevant qe-to-GDP measure should reduce the 10-year bond yield by 53, 43 and 15 bps respectively.

We next present estimation results using GMM as the estimation method to address possible endogeneity problems. In the presence of endogenous variables, GMM is known to yield consistent estimates of the parameters. GMM estimates are reported in Table 4, columns 4 to 6; they are very similar to those obtained under OLS estimation. The instruments used in estimation are the second lag of the long-term interest rate and the first and second lags of real potential GDP, the monetary base and the monetary aggregate M2 (all in logs). The Hansen's J-test for instrument validity indicates that the model is correctly specified and all instruments are exogenous. The results of the Arrelano-Bond test for first to third order autocorrelation of the residuals suggest that this assumption can be rejected. In addition, we apply the Kleinbergen-Paap weak identification test as a first-stage estimation and we find F statistics for all three cases which are higher than the value suggested by the Staiger and Stock's rule of thumb, that is 10. Further, we apply the Kleinbergen-Paap rank test for the model under-identification under the null hypothesis that the rank of the matrix of cross products between the endogenous regressors and the instruments is zero, which is rejected.

5.3 Bond premium puzzles

Our model appears to account pretty well for two puzzling episodes in the sample period that were discussed widely in the literature. The first is the "bond yield conundrum",[38] according to which there has been unusual directional divergence between short- and long-term rates during the 2004-6 tightening of US monetary policy: the ten-year Treasury bond yield fell in this period, while the federal funds rate rose from 1 percent in June 2004 to 5 1/4 percent in December 2006. Rudebusch (2010) suggested that to determine whether long-term interest rate movements represent a genuine puzzle requires a theoretical framework that takes into account the various factors that influence long-term rates and that a macro-finance perspective appears well suited to such an investigation. In fact, Rudebusch et al. (2006) used two empirical no-arbitrage macro-finance models of the term structure of interest rates that, however, failed to explain the puzzle. The further use in these models of additional variables, particularly the decline in bond rate volatility, were found to explain a portion but not all of the conundrum. As Figure 5 shows, our model provides a very good fit to the data, including the period 2004 through 2006 featuring the bond yield conundrum.

[Insert Figure 5 here]

The second puzzling issue is the so-called "bond premium puzzle" (Backus et al., 1989), which describes the broader inability of standard theoretical models to generate a sufficiently large and variable bond term premium. In this respect, Rudebusch and Swanson (2008) show that in simple DSGE models used in macroeconomics the term premium on long-term bonds is small and stable relative to the data; extending these DSGE models to more fully specified versions, by introducing, for instance habits in consumption or nominal rigidities, helped the models to account for the term premium but only by affecting their ability to fit other macroeconomic variables. Other modifications, for example using the Epstein-Zin preferences, appear useful in letting DSGE models replicate certain bond pricing facts without compromizing their ability to fit macroeconomic developments although these models remain too rudimentary in terms of the specification of their financial sector. A final remark made by Rudebusch (2010) is that no existing model, be it a term structure model or a DSGE model, seems to specify the linkages between bond supply and the term premium at times of unconventional monetary policy and is not therefore able to provide a solution to the bond premium puzzle. Our macro-finance model of the bond yield, by incorporating

[38] The bond yield conundrum has been labeled so by the former Fed's Chairman Alan Greenspan in his February 17, 2005 testimony before the Committee on Banking, Housing, and Urban Affairs of the US Senate.

the relationship between quantitative easing variables and the term premium, can be seen as an important step allowing us to also account for the bond premium puzzle.

5.4 Analyzing the effects of quantitative easing and balance sheet normalization on long-term interest rates

As discussed in section 5.2, the consensus view favors, as our empirical results also do, a very gradual adjustment of the long-term rate toward the long-run level. This is of particular interest regarding the long-run effects of changes in the quantitative easing variables on the bond yield. For this reason, Table 5 provides a comparative presentation of the short- and the long-run effect of the alternative qe measures employed in estimation. Long-run estimated effects have been derived on the basis of the short-run effects divided by the speed of adjustment parameter; they are found to be of high magnitude, especially in the case of the first two qe variables, suggesting that if the increase in the qe variable was sustained, then eventually the effect would be -298, -246 and -118 bps, respectively.

[Insert Table 5 here]

Table 6 provides a summary of empirical literature including an overall quantification of the effect of the Fed's asset purchase programs on the 10-year government bond yield or the term premium either in terms of an estimated cumulative decline or as an elasticity for large-scale qe measures. In the reported studies, the estimated cumulative effect of the Fed's asset purchases on the 10-year government bond yield/term premium broadly varies between 100 and 150 bps. Bonis et al. (2017) further outline a projected path for the gradual de-escalation of the term premium effect on the bond yield after the end of reinvestments and the start of the Fed's balance sheet normalization. They estimate that the initial decline of 100 bps in the term premium would be reduced by 15 bps as the time for a change in the reinvestment policy came nearer. Even after full balance sheet normalization, they estimate a remaining 24 bps negative effect on the term premium, reflecting a still different portfolio composition in the Fed's asset holdings toward longer-term assets. Gagnon et al. (2011) also distinguish between a short-run and a long-run effect of changes in the long-term debt supply to the private sector on the term premium; however, the quantitative difference between the two effects appears to be very small.

[Insert Table 6 here]

As it has been analytically presented in Section 2, the implementation of the Fed's asset purchase programs has been a dynamic process which can be broadly distinguished into three phases: the first captures the active Fed balance sheet expansion, comprising three LSAPs, two MEPs and two reinvestment programs, lasting from end-2008 to end-2014; the second phase reflects the conclusion of net asset purchases and continuation only of reinvesting (in full) the principal payments on maturing securities, the phase lasting from end-2014 to end-2017; and the third one coincides with the balance sheet normalization process through the gradual reduction in aggregate Fed's securities holdings, which lasts from end-2017 until the end of our sample period in the third quarter of 2019.

Specifically, during the Fed's balance sheet expansion period, i.e. from 2008q3, just before the initiation of LSAP1, until early 2014q4, when net asset purchases were concluded, the monetary base grew roughly by $3 trillion (from 6% of GDP to almost 23%), a rise which according to our estimates presented in Table 7, should have reduced the term premium component of yields by 69 basis points. The respective increase in the Fed's securities portfolio amounted to almost $ 4 trillion (from 3% to 25% of GDP) and is estimated to have been translated into an 88 basis points bond yield reduction. The $ 2.7 trillion (from 1% to 16% of GDP) rise in bank reserves should have led respectively to a 40 bps reduction in the bond yield during the balance sheet expansion period. The subsequent period of maintaining only the existing reinvestment policy that lasted until October 2017 should have led, according to our estimates, to an overall limited increase in bond yields by around 9 bps and 4 bps. This small rise could reflect the fact that, as the Fed's securities holdings were approaching maturity, there were growing expectations for a possible unwinding of policy accommodation in the near future. Thereafter, and roughly until the end of our data period, the Fed reduced its securities holdings by gradually decreasing reinvestments of principal payments. During this period the monetary base decreased by $ 700 bn (to 15% of GDP), the Fed's securities portfolio also fell by almost 700 bn (to 17% of GDP) and bank reserves declined by around $ 850 billion (to 7% of GDP). Accordingly, the policy of balance sheet normalization should have resulted in a total rise of 15, 10 and 8 bps in bond yields under each alternative measure of qe, before its conclusion in August 2019.

The respective long-run effects point to a substantial decrease in long-term bond yield during the balance sheet expansion period, ranging between 319 and 498 bps. For the reinvestments-only period, the yield rise ranges between 24 and 52 bps in the long run, while for the balance-sheet normalization period the respective increase in the bond yield varies between 57 and 85 bps respectively. Comparing our results to those in the literature, we observe that our estimated impact of qe_1 and qe_2 is broadly comparable to those of Bonis et al. (2017), Ihrig et al. (2018), Swanson (2015) and Gagnon et al. (2011) for the term premium, even more so in the case of qe_2; the qe_3 effect stands at a considerably lower level. However, our estimated long-run effect of qe considerably exceeds the respective estimate of Gagnon et al. (2011).

[Insert Table 7 here]

6. Estimates of the equilibrium real interest rate

The long-term interest rate equation which we estimated above can be used to arrive at an estimate of the real interest rate in equilibrium (or natural rate of interest). Estimates of the equilibrium real interest rate are of central importance for monetary policy as they provide a gauge for the “long-run neutral” monetary policy stance: real rates standing above or below the equilibrium rate would suggest a contractionary or expansionary policy as they would tend to slow down or stimulate economic growth (Williams, 2003; Ferguson, 2004; Kiley, 2020). The equilibrium real rate is defined as the rate consistent with full utilization of resources in the economy and price stability (see e.g. Yellen, 2015). This definition of the equilibrium real rate takes a long-run perspective (Williams, 2003). The long run is a period of sufficient length to allow all variables in the economy to settle at constant levels in the absence of new economic disturbances.

As already discussed, the equilibrium real interest rate may change over time as a result of persistent shifts in aggregate supply or demand arising from real factors such as those affecting the growth rate of potential output or aggregate spending in the economy and which are outside the control of the central bank (Clarida, 2019). A downward trend was identified in estimates of the equilibrium real interest rate, which is a rather robust finding across different studies with different methodologies and across advanced economies (Williams, 2003; Laubach and Williams, 2016; Kiley, 2020; López-Salido et al., 2020). Bauer and Rudebusch (2020) argue that the very high persistence observed in interest rates, which reflects a slow-moving trend component, is explained by quantitatively important downward trends in the equilibrium real interest rate (r*) and inflation (π*) – that is an environment of "falling stars".

Two issues are important in our discussion of the equilibrium real interest rate. First, the vast majority of empirical work estimates the equilibrium real interest rate in terms of the federal funds rate, and this is distinct from the equilibrium real interest rate on long-term government debt or corporate debt, although those rates are expected to be related to the equilibrium real federal funds rate (Hamilton et al., 2016). Cukierman (2016) suggests that increasing attention should be paid to the long-term risky interest rate, and therefore to the natural counterpart of this rate, since existing estimates of the natural rate based on riskless assets are likely to be biased downward. Roberts (2018) focuses on the long-term interest rate for the estimation of the equilibrium real rate by noting that central banks in the wake of the financial crisis were constrained by limits on how much they could reduce short-term interest rates, and thus turned to policies affecting long-term interest rates, such as longer-term asset purchases. Also, he notes that the importance of deriving an estimate of the equilibrium long-term real rate is highlighted in the context of many macroeconomic models where long-term interest rates are considered to be more important for spending decisions in the economy than short-term rates. Our measure of the equilibrium real rate can be seen as referring to a long-term rate. Second, estimates of the equilibrium real interest rate are either based on single-variable methods or are model-based. The former focus on long-run values, examining the behavior of the real interest rate over long periods of time (e.g. Hamilton et al., 2016). Model-based studies use mostly versions of the New Keynesian model or similar frameworks that are generally characterized by the absence of financial frictions. Roberts for example uses an aggregate demand equation similar to the one encountered in the New Keynesian model to estimate the neutral (natural) rate of interest. Also, Laubach and Williams (2003) opt for a single-equation approach to estimate the equilibrium real federal funds rate, using the Kalman filter to extract the persistent component of the equilibrium interest rate, while Holston et al. (2017) extend this analysis to a number of advanced economies. As already noted, our estimated macro-finance model will be the basis for calculating the equilibrium real interest rate.

[Insert Figure 6 here]

For the purpose of deriving an estimate of the equilibrium real interest rate, which is a long-run concept, we need to focus correspondingly on the long-run behavior of our model, allowing for time variation of the equilibrium rate and removing cyclical influences on the interest rate (Williams, 2015). Specifically, we obtain the long-run static equilibrium of our model by suppressing time subscripts of all variables and imposing the equality between output and potential output, which is an essential element of the definition of r*.[39] Also, the static equilibrium values of inflation and interest rate uncertainty are by definition zero. In this respect, by taking into account the estimated long-run parameters, we can think of the equilibrium real interest rate as the sum of the following three components: the model's constant term, the effect of the time trend included in the specification, and, finally, the effect of the trend of the monetary base-to-GDP ratio, which is part of our qe variable in the first of the three alternative definitions of this variable. Regarding this last variable, we need to account only for the part of this ratio that pertains to the long run and remains unaffected by the conduct of monetary policy. Thus for the period after the last quarter of 2008, when there was a significant jump in the monetary base as a result of the start of large-scale asset purchases by the Federal Reserve and the implementation of monetary policy in a regime of ample reserves, we transformed the above ratio so as to reflect only the trend characterizing it for the period prior to the fourth quarter of 2008, and by extending this trend thereafter. In this way, we attempt to account only for the part of the monetary base-to-GDP ratio that does not reflect the conduct of monetary policy. Conceptually, this trend should capture the intuitive notion that the monetary base that is readily available in the economy, in terms of both cash and highly liquid bank reserve balances, in the long run should roughly co-move with economic activity.[40]

According to the above estimates, the equilibrium real interest rate, as presented in Figure 6, shows a declining path over time, which becomes milder during 2004-2007. The equilibrium real rate ranges from 3.9 percent at the end of the 1980s to 1.3 percent in early 2008. During 2008, there is a substantial decline of around 40 basis points and thereafter it continues on a downward path until mid-2012. Since then, this downward

[39] The equality between output and potential output could be part of the long-run solution of a larger-scale model (see for example Brissimis and Leventakis, 1984; Balfoussia et al., 2011).
[40] In their estimations for the term premium effect of the Fed's securities holdings, Bonis et al., (2017) also assume that the size of the Fed's balance sheet would be normalized when the securities portfolio reverted to the level consistent with its longer-run trend; this trend is largely determined by currency in circulation and a projected long-run level of reserve balances.

trend seems to slow down and the equilibrium rate reaches 0.2 percent at the end of the sample period.

Figure 6 also presents for comparison two other measures of the equilibrium real interest rate derived within a model that employs forward- rather than backward-looking measures of inflation expectations (López-Salido et al., 2020). A common finding of all measures is that the equilibrium real interest rate shows a downward trend reaching in the last decade a level not seen for years. However, although for the time period up to 2008 all measures have been broadly following the same path, measures based on inflation expectations show more fluctuations than our measure. With the eruption of the financial crisis in 2008, the estimates of the equilibrium rate using inflation expectations record a much steeper fall of around 120 bps, turning actually negative from 2009 onward. A further distinguishing feature of our estimate is that it is uniformly higher than the other two measures in the post-crisis period, the difference between them being of the order of 1 percent.

7. Conclusions

In this paper, we develop a comprehensive analytical framework for studying the behavior of long-term interest rates. This is accomplished in the context of a term structure model that is based on the expectations hypothesis extended to include a time-varying risk premium and combines both a macroeconomic and a finance perspective. Interest in understanding movements in the term structure has resurged in the last two decades in view of low real interest rates and central bank unconventional policy responses to the 2008 financial crisis, after short-term rates had reached the ZLB.

Based on the standard finance model of the EH extended to include a time-varying term premium, we show that the yield curve is a useful tool for analyzing central bank behavior, and the effects of quantitative easing policies in particular. Specifically, our macro-finance term structure model encompasses the link between the expected path of short-term rates and inflation, the output gap and the equilibrium real interest rate, as well as the link between the term premium and short-term rate volatility and unconventional quantitative-easing monetary policy. Particular attention has been drawn to the role of interest rate persistence and macroeconomic trends in understanding the dynamics of interest rates. We provide evidence for statistically significant effects of these variables in explaining variations in long-term interest rates.

To estimate monetary easing effects on the term premium, alternative measures from the central bank balance sheet have been employed (the monetary base, the Fed's portfolio of securities or bank reserves), allowing us to effectively capture the total impact of all phases of unconventional balance sheet policy implementation (expansion, stabilization and normalization), while further insights are provided by distinguishing between the short-run and long-run effects of changes in these variables on bond yields.

Applied to the US long-term Treasury bond yields in order to evaluate the Federal Reserve's asset purchase programs, the model provides an excellent empirical fit, while it succeeds in addressing the bond-yield conundrum in 2004-2005 and the broader bond premium puzzle referred to in the literature. Thus, by incorporating the relationship between quantitative easing variables and the term premium, the model represents an important step toward accounting for these puzzles. Further, according to our estimates, a one-unit increase in the relevant qe-to-GDP ratio should reduce the 10-year bond yield by 53, 43 and 15 bps depending on the central bank balance sheet measure employed each time, while, if the increase is sustained, these effects could reach up to 300, 250 and 120 bps respectively in the long run. In particular, the Fed's asset purchases actually reduced the 10-year US Treasury bond yield by around 70, 90 or 40 bps respectively in the balance sheet expansion phase which subsequently unfolded by almost 25, 14 or 12 bps respectively in the reinvestment-only and normalization phases up to the end of our sample period.

Furthermore, by focusing on the long-run behavior of the model, we derived an estimate of the equilibrium real interest rate that successfully captures the declining trend embedded in real interest rates over the last decades and presents the innovation that it incorporates the evolution of the central bank balance sheet to the extent consistent with its longer-run, pre-crisis trend. According to this estimate, the equilibrium real interest rate stood at 3.8% in 1989 and declined to 1.1% right before the 2008 financial crisis and further to 0.2% at the end of our data period in 2019.

The framework developed hereto provides, inter alia, for the link between quantitative easing monetary policy and the term premium that constituted an additional tool for central banks at the ZLB. In this respect, it would seem natural to extend this paper by incorporating it into a broader New Keynesian or DSGE model that allows for financial frictions enhancing our understanding of the links between asset prices, interest rates, output and inflation.

Appendix A

CHRONOLOGY OF FEDERAL RESERVE'S ASSET PURCHASE PROGRAMS (2008-2019)

Programme	Type of assets	Size	Start	End
I) Balance sheet expansion				
Large-Scale Asset Purchases 1 (LSAP1)	Agency debt Agency MBS	\$ 200 bn \$ 1,250 bn	Dec. 2008	Mar. 2010
	Longer-term Treasury securities	\$ 300 bn	Mar. 2009	Oct. 2009
Reinvestment of principal payments from agency debt and agency MBS in longer-term Treasury securities - roll over of maturing Treasury securities	Longer-term Treasury securities		Aug. 2010	Sept. 2011
Large-Scale Asset Purchases 2 (LSAP2)	Longer-term Treasury securities	\$ 600 bn	Nov. 2010	June 2011
Maturity Extension Program 1 (MEP1)	Treasury securities of remaining maturity 6-30 years to substitute for Treasury securities of remaining maturity <3 years	\$ 400 bn	Sept. 2011	June 2012
Reinvestment of principal payments from agency debt and agency MBS in agency MBS and roll over of maturing Treasury securities	Agency MBS		Sept. 2011	Oct. 2017
	Treasury securities (roll over)		Sept. 2011 Jan. 2013	June 2012 Oct. 2017
Maturity Extension Program 2 (MEP2)	Treasury securities of remaining maturity 6-30 years to substitute for Treasury securities of remaining maturity <3 years	\$ 267 bn	June 2012	Dec. 2012
Large-Scale Asset Purchases 3 (LSAP3)	Agency MBS Longer-term Treasury securities	\$40 bn/month \$45 bn/month	Sept. 2012 Jan. 2013	(open-ended)
Gradual cuts in the pace of monthly purchases (by \$5 bn after each FOMC meeting)	Agency MBS Longer-term Treasury securities	starting from \$35 bn/month \$40 bn/month	Jan. 2014	Oct. 2014
Conclusion of asset purchases - continuation of reinvestment policy	Maintaining existing policy of reinvesting principal payments from agency debt and agency MBS in agency MBS and roll over of maturing Treasury securities		Oct. 2014	Oct.2017

Programme	Type of assets	Size	Start	End
II) Balance sheet normalization				
Policy Normalization Principles and Plans - Key elements, augmentation of the normalization approach			June 2011 Sept. 2014 Mar. 2015 June 2017	
Announced start of balance sheet normalization from Oct. 2017	- Gradual reduction of the Fed's securities holdings - Principal payments reinvested only to the extent that they exceeded specific gradually rising caps		Sept. 2017	
Balance sheet normalization	- Cap for reinvestments in Treasury securities: $6 bn/month initially, increasing in steps of $6 bn at three-month intervals over 12 months, up until $30 bn/month - Cap for reinvestments in agency debt and agency MBS: $4 bn/month initially, increasing in steps of $4 bn at three-month intervals over 12 months, up until $20 bn/month		Oct. 2017	Apr. 2019
	- Slowing the pace of reduction of Treasury holdings by reducing the cap on monthly redemptions from $30 bn/month to $15 bn/month		May 2019	July 2019
	- Treasury securities rolled over in full		Aug. 2019	
Conclusion of reducing aggregate Fed's securities holdings			Aug. 2019	
III) Longer-run monetary policy regime				
Ample supply of reserves ensuring control over the level of the fed funds rate exercised primarily through the setting of the Fed's administered rates, no active management of reserve supply			Jan. 2019	
Gradual reduction in agency debt and agency MBS holdings with an aim of holding primarily Treasury securities in the longer run	- Treasury securities rolled over in full - Principal payments from agency debt and agency MBS reinvested in Treasury securities subject to a maximum amount of $ 20 bn/month; principal payments in excess of this amount continue to be reinvested in agency MBS - Agency debt and agency MBS reinvested in Treasuries will roughly match the maturity of Treasury securities outstanding - Limited sales of agency MBS possible		Aug. 2019	
Technical measures to ensure ample supply of reserves in view of increases in non-reserve liabilities	- Purchase of Treasury bills to maintain the level of reserves of early Sep.2019 (or a higher level) - Term and overnight repos		Oct. 2019	At least up to Q2 2020

Source: Board of Governors of the Federal Reserve System.

Appendix B

Derivation of the interest rate policy rule

By its interest rate decisions, the central bank aims at minimizing its intertemporal quadratic loss function, which is assumed to comprise two arguments, inflation and output gap stabilization:

$$L_t = \frac{1}{2} E_t \sum_{j=0}^{\infty} \beta^j [\, \pi_t^2 + \varphi x_t^2] \quad \text{(A1)}$$

where E_t denotes expectations conditional upon information available at time t, β is the discount factor with $0 < \beta < 1$, and φ is the parameter representing the weight on output gap stabilisation relative to inflation stabilisation around a long-run inflation target which is assumed to be zero.[41] Parameter φ is expected to range from 0 to 1 and be closer to 0 when price stability is the main objective of the central bank. The central bank aims at minimising the expected sum of discounted squared future deviations of inflation and output from the inflation target and the potential level respectively, subject to the constraint represented by a forward-looking aggregate supply curve of the New-Keynesian type:

$$\pi_t = \beta \pi_{t+1\,|\,t} + a_1 x_t + e_{pt} \quad \text{(A2)}$$

where π_t is the inflation rate, $\pi_{t+1\,|\,t}$ is the expectation of period t+1 inflation rate conditional on a time t information set, x_t is the output gap and e_{pt} is a supply/cost-push shock assumed to be i.i.d. with constant variance σ_{pt}^2. The discount factor β reflects the sensitivity of current inflation to expected inflation with 0 < β < 1, while α_1 represents the sensitivity of inflation to output gap changes, with $\alpha_1 > 0$.

The central bank also considers the additional conditions provided by a forward-looking aggregate demand equation of the form:

$$x_t = x_{t+1\,|\,t} - b_1 \left[i_t - \pi_{t+1\,|\,t} \right] + b_0 + e_{yt} \quad \text{(A3)}$$

where $x_{t+1\,|\,t}$ is the expectation of period t+1 output gap conditional on a time t information set, where b_1 measures the response of the output gap to the real interest rate with $b_1 > 0$, $b_0 = b_1 \rho$ and $\rho = -ln(\beta)$, ρ is the (exogenous) natural rate of interest and e_{yt} is a demand shock assumed to be i.i.d. with constant variance σ_{yt}^2. By setting the policy rate, the central bank aims at affecting the real short-term rate, and thus the optimal path for output. Thus, the aggregate demand equation indicates the degree of control over the economy available to the central bank.

The Lagrangian for this problem is of the form :

$$\int = \sum_{j=0}^{\infty} \beta^j \left(\frac{1}{2} \, (\pi_t^2 + \varphi x_t^2) \right) + \gamma_t \, (\pi_t \; - \beta \, \pi_{t+1} - \alpha_1 x_t \;) \quad \text{(A4)}$$

[41] See also Svensson (1997), Clarida et al. (1999) and Woodford (2003).

where γ_t is the Lagrange multiplier associated with the period t aggregate supply equation. Differentiation of the Lagrangian with respect to each of its arguments, yields the first order conditions for any $t \geq 0$:

$$\pi_t + \gamma_t - \gamma_{t-1} = 0 \tag{A5}$$

$$\varphi x_t - \alpha_1 \gamma_t = 0 \tag{A6}$$

In A5, for $t = 0$, $\gamma_{-1} = 0$, as there is in fact no constraint associated with the fulfilment of a period-minus-one aggregate supply relation (Galí, 2015; Woodford, 2003). By eliminating γ_t from A5 and A6, we get the consolidated first-order condition:

$$\varphi x_t + \alpha_1 \pi_t = 0 \tag{A7}$$

or

$$\pi_t = -\frac{\varphi}{\alpha_1} x_t \tag{A8}$$

To obtain a reduced-form expression for x_t , we combine the optimality conditions with the aggregate supply equation and get :

$$-\frac{\varphi}{\alpha_1} x_t \quad = a_1 x_t + \beta \pi_{t+1|t} + e_{pt} \tag{A9}$$

or

$$x_t \quad = -\frac{\beta a_1}{\varphi + {a_1}^2} \pi_{t+1|t} + \frac{a_1}{\varphi + {a_1}^2} e_{pt} \tag{A10}$$

Similarly for π_t , we get:

$$\pi_t = \frac{\varphi \beta}{\varphi + {a_1}^2} \pi_{t+1|t} + \frac{\varphi}{\varphi + {a_1}^2} e_{pt} \tag{A11}$$

By substituting (A10) into the aggregate demand equation and solving for i_t, we get the expression for the monetary policy interest rate rule:

$$i_t = \frac{b_0}{b_1} + \frac{1}{b_1} x_{t+1|t} + \left(1 + \frac{\beta a_1}{b_1(\varphi + {a_1}^2)}\right) \pi_{t+1|t} - \frac{a_1}{\varphi + {a_1}^2} e_{pt} + \frac{1}{b_1} e_{yt} \tag{A12}$$

Appendix C

The interest rate rule and the term structure of interest rates

The interest rate rule as expressed in A12, can be written as:

$$i_t = \frac{b_0}{b_1} + \frac{1}{b_1} x_{t+1|t} + \left(1 + \frac{A}{b_1}\right) \pi_{t+1|t} \qquad \text{(B1)}$$

where $A = \frac{\beta\, \alpha_1}{(\varphi + a_1{}^2)} > 0$ and $b_0 = b_1 \rho$ and $\rho = -ln(\beta)$.

As in Ellingsen and Södertsröm (2001), we lead the interest rate rule s periods ahead and take expectations, which yields:

$$i_{t+s|t} = \frac{b_0}{b_1} + \frac{1}{b_1} x_{t+s+1|t} + \left(1 + \frac{A}{b_1}\right) \pi_{t+s+1|t} \qquad \text{(B2)}$$

The expected output process for s ≥ 1 periods from now, is obtained by leading the aggregate demand equation s periods ahead and taking expectations as follows:

$$x_{t+s|t} \quad = x_{t+s+1|t} - b_1 \left[i_{t+s|t} - \pi_{t+s+1|t} \right] + b_0 \qquad \text{(B3)}$$

After substituting B2 into B3, we finally get:

$$x_{t+s|t} \quad = -A\, \pi_{t+s+1|t} \qquad \text{(B4)}$$

Similarly, the expected path for inflation for s ≥ 1 periods into the future is given by:

$$\pi_{t+s|t} = \beta \pi_{t+s+1|t} + a_1 x_{t+s|t} \qquad \text{(B5)}$$

or, given (B4), by

$$\pi_{t+s|t} \quad = (\beta - a_1 A)\, \pi_{t+s+1|t} \qquad \text{(B6)}$$

It can be easily established by repeated substitution that expected inflation will follow the geometric series:

$$\pi_{t+s+1|t} = \frac{1}{(\beta - a_1 A)} \pi_{t+s|t} \qquad \text{(B7)}$$

or

$$\pi_{t+s+1|t} = \frac{1}{(\beta - a_1 A)^s} \pi_{t+1|t} \qquad \text{(B8)}$$

or

$$\pi_{t+s+1|t} = \frac{1}{(\beta - a_1 A)^s} \left(\frac{1}{\beta} \pi_t - \frac{a_1}{\beta} x_t\right) \qquad \text{(B9)}$$

Similarly, for expected output we get:

$$x_{t+s+1|t} = -A \pi_{t+s+2|t} \qquad \text{(B10)}$$

or

$$x_{t+s+1|t} = -A \left[\frac{1}{(\beta - \alpha_1 A)^{s+1}}\right] \left(\frac{1}{\beta} \pi_t - \frac{a_1}{\beta} x_t\right) \qquad \text{(B11)}$$

The expected output gap one-period ahead can be written as:

$$x_{t+1|t} \quad = -A\, \pi_{t+2|t} \qquad \text{(B12)}$$

or

$$x_{t+1\,|\,t} \quad = -A\ \left[\frac{1}{(\beta-\alpha_1 A)}\right]\pi_{t+1\,|\,t} \tag{B13}$$

or

$$x_{t+1\,|\,t} \quad = -A\ \left[\frac{1}{(\beta-\alpha_1 A)}\right]\left(\frac{1}{\beta}\pi_t - \frac{a_1}{\beta}x_t\right) \tag{B14}$$

Expected inflation one-period ahead can be written as:

$$\pi_{t+1\,|\,t} \quad = (\beta - a_1 A)\,\pi_{t+2\,|\,t} \tag{B15}$$

or

$$\pi_{t+1\,|\,t} \quad = (\beta - a_1 A)\ \left[\frac{1}{(\beta-\alpha_1 A)}\right]\pi_{t+1\,|\,t} \tag{B16}$$

or

$$\pi_{t+1\,|\,t} \quad = \left(\frac{1}{\beta}\pi_t - \frac{a_1}{\beta}x_t\right) \tag{B17}$$

By substituting $x_{t+1\,|\,t}$ and $\pi_{t+1\,|\,t}$ in the interest rate rule (B1) we get:

$$i_t = \frac{b_0}{b_1} + \left[-\frac{A}{b_1(\beta-\alpha_1 A)} + (1+\frac{A}{b_1})\right]\left(\frac{1}{\beta}\pi_t - \frac{a_1}{\beta}x_t\right) \tag{B18}$$

By substituting $x_{t+s+1\,|\,t}$ and $\pi_{t+s+1\,|\,t}$ in (B2), the expected future short-term interest rate s periods ahead is given by:

$$i_{t+s\,|\,t} = \frac{b_0}{b_1} + \quad \frac{1}{(\beta-a_1 A)^s}\left[1+\frac{A}{b_1}\left(1-\frac{1}{\beta-\alpha_1 A}\right)\right]\left(\frac{1}{\beta}\pi_t - \frac{a_1}{\beta}x_t\right) \tag{B19}$$

and its sum over the period t+1 to t+n-1 is obtained as follows:

$$\sum_{s=1}^{n-1} i_{t+s\,|\,t} = (n-1)\frac{b_0}{b_1} + \left[1+\frac{A}{b_1}\left(1-\frac{1}{\beta-\alpha_1 A}\right)\right]Z^n(\frac{1}{\beta}\pi_t - \frac{a_1}{\beta}x_t) \tag{B20}$$

where $Z^n = \frac{1-\frac{1}{(\beta-\alpha_1 A)^{n-1}}}{1-\frac{1}{(\beta-\alpha_1 A)}} = 1 - \frac{\beta-\alpha_1 A}{(\beta-\alpha_1 A)^{n-1}} > 0$.

Finally, by using the interest rate rule (B1) and (B2) and the sum (B20) in the expectations hypothesis of the term structure of interest rates, we get:

$$i_t^n = \frac{1}{n}\sum_{s=0}^{n-1} i_{t+s\,|\,t} + tp_t^n \tag{B21}$$

or

$$i_t^n = \frac{1}{n}i_t \quad + \frac{1}{n}\sum_{s=1}^{n-1} i_{t+s\,|\,t} + tp_t^n \tag{B22}$$

or

$$\begin{aligned} i_t^n = \frac{b_0}{b_1} + \frac{1}{n}\left[\left(\frac{A}{b_1}\left(1-\frac{1}{\beta-\alpha_1 A}\right)+1\right)\left(\frac{1}{\beta}\pi_t - \frac{a_1}{\beta}x_t\right)\right] + \\ \frac{1}{n}\left[(1+\frac{A}{b_1}\left(1-\frac{1}{\beta-\alpha_1 A}\right))Z^n(\frac{1}{\beta}\pi_t - \frac{a_1}{\beta}x_t)\right] + tp_t^n \end{aligned} \tag{B23}$$

or

$$i_t^n = \frac{b_0}{b_1} + \frac{1}{n}\left(1+\frac{A}{b_1}\left(1-\frac{1}{B}\right)\right)(1+Z^n)\left((\frac{1}{\beta}\pi_t - \frac{a_1}{\beta}x_t)\right) + tp_t^n \tag{B24}$$

where Z^n=$1 - \frac{B}{B^{n-1}} > 0$ and $B = \beta - \alpha_1 A = \frac{\beta\varphi}{\varphi + a_1{}^2} > 0$.

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Tables and Figures

Table 1 – Variables used in the empirical analysis

Variable	Notation	Measure	Data source
Long-term interest rate	i	10-year Treasury bond yield (%)	Board of Governors of the Federal Reserve System
Inflation rate (annualized)	π	Difference in the GDP deflator (in log, %)	US Bureau of Economic Analysis
Output gap	x	Difference between real GDP and real potential GDP (in logs, %)	US Bureau of Economic Analysis US Congressional Budget Office
Interest rate uncertainty	unc	Merrill Lynch Move index of bond market volatility	Thomson Reuters Datastream
Quantitative easing (as a ratio of nominal GDP, in logs)	qe	1) Monetary base 2) Securities held by the Federal Reserve System 3) Total reserves of depository institutions	Board of Governors of the Federal Reserve System US Bureau of Economic Analysis

Table 2 – Descriptive statistics (1988Q4-2019Q3)

	i	π	x	unc	qe_1	qe_2	qe_3
Mean	4.67	2.06	-1.32	94.19	-2.46	-2.56	-3.84
Median	4.54	2.08	-1.04	94.65	-2.78	-2.91	-4.55
Maximum	9.36	4.46	2.34	216.90	-1.47	-1.36	-1.82
Minimum	1.62	-0.58	-6.20	46.70	-3.04	-3.43	-5.08
Std. Dev.	2.04	0.94	1.93	26.82	0.55	0.68	1.20
Skewness	0.34	-0.07	-0.43	1.01	0.69	0.73	0.63
Kurtosis	2.12	3.60	2.52	5.91	1.71	1.78	1.54
Observations	124	124	124	124	124	124	124

Table 3 – Unit root tests

Table 3A ADF-test results

Variables	H_1: the series is stationary	H_1: the series is stationary around a constant term	H_1: the series is stationary around a trend
i	-1.93 *	-1.60	-4.07 ***
π	-1.77	-5.50 ***	-6.11 ***
x	-2.12 **	-2.53	-2.44
unc	-1.20	-4.45 ***	-4.90 ***
qe_1	-1.64 *	-0.59	-1.42
qe_2	-1.28	-0.62	-2.73
qe_3	-1.00	-0.84	-1.75

Notes: ADF statistics reported. The null hypothesis H_0 in all tests is that the series has a unit root/is nonstationary. The alternative hypothesis H_1 is quoted respectively in the three different forms of the test. (*), (**), (***) denote statistical significance at the 10%, 5% and 1% level respectively.

Table 3B ADF-test results (with a breakpoint)

Variable (breakpoint date)	H_1: the series is stationary around a constant term with a breakpoint in the constant term	H_1: the series is trend stationary with a breakpoint in the constant term	H_1: the series is stationary around a trend with a breakpoint in the constant term and the trend
qe_1 (2008 Q3)	-8.09 ***	-8.04 ***	-5.06 *
qe_2 (2008 Q4)	-9.33 ***	-8.96 ***	-6.45 ***
qe_3 (2008 Q3)	-10.00 ***	-13.48 ***	-11.46 ***

Notes: ADF statistics reported. The null hypothesis H_0 in all tests is that the series has a unit root/is nonstationary. The alternative hypothesis H_1 is quoted respectively in the three different forms of the test. (*), (**), (***) denote statistical significance at the 10%, 5% and 1% level respectively.

Table 4 – Estimation results

	OLS			GMM		
	(1)	(2)	(3)	(4)	(5)	(6)
c_0	-0.93***	-0.66***	-0.51***	-0.96***	-0.69***	-0.56***
	(0.23)	(0.16)	(0.16)	(0.24)	(0.17)	(0.16)
π_t	0.09**	0.10**	0.09*	0.09**	0.09**	0.08*
	(0.05)	(0.05)	(0.05)	(0.04)	(0.04)	(0.05)
x_t	0.29***	0.35***	0.30***	0.30***	0.33***	0.29***
	(0.06)	(0.07)	(0.06)	(0.06)	(0.07)	(0.06)
x_{t-1}	-0.31***	-0.36***	-0.31***	-0.32***	-0.35***	-0.31***
	(0.06)	(0.07)	(0.06)	(0.06)	(0.07)	(0.06)
unc_{t-1}	$4.02*10^{-3}$**	$3.11*10^{-3}$*	$4.50*10^{-3}$**	$4.04*10^{-3}$**	$3.34*10^{-3}$*	$4.44*10^{-3}$**
	($1.80*10^{-3}$)	($1.84*10^{-3}$)	($1.85*10^{-3}$)	($1.73*10^{-3}$)	($1.77*10^{-3}$)	($1.80*10^{-3}$)
$qe_{1,t}$	-0.53***			-0.53***		
	(0.18)			(0.19)		
$qe_{2,t}$		-0.43***			-0.42***	
		(0.15)			(0.15)	
$qe_{3,t}$			-0.15**			-0.15**
			(0.07)			(0.07)
i_{t-1}	0.82***	0.82***	0.87***	0.82***	0.83***	0.88***
	(0.04)	(0.04)	(0.04)	(0.05)	(0.05)	(0.04)
t	$-4.59*10^{-3}$***	$-4.73*10^{-3}$***	$-3.92*10^{-3}$***	$-4.44*10^{-3}$***	$-4.58*10^{-3}$***	$-3.78*10^{-3}$***
	($1.48*10^{-3}$)	($1.53*10^{-3}$)	($1.51*10^{-3}$)	($1.45*10^{-3}$)	($1.50*10^{-3}$)	($1.44*10^{-3}$)
Observations	123	123	123	123	123	123
R-squared	0.96	0.96	0.96	0.96	0.96	0.96
Standard errors	Robust	Robust	Robust	Robust	Robust	Robust
Tests						
Hansen J-test	-	-	-	0.17	0.15	0.10
Weak identification test	-	-	-	68.68	79.35	108.93
Under-identification test	-	-	-	0.00	0.00	0.00
Arellano-Bond for AR(1)	0.47	0.48	0.70	0.45	0.49	0.53
Arellano-Bond for AR(2)	0.37	0.25	0.27	0.39	0.36	0.35
Arellano-Bond for AR(3)	0.66	0.66	0.69	0.39	0.40	0.38

Notes: Dependent variable is the 10-year government bond yield; (*), (**), (***) denote significance at the 10%, 5% and 1% level, respectively. Standard errors are reported in parentheses. Diagnostics: Hansen J-test (p-value) examines whether instruments are valid (null); Two Kleibergen-Paap tests examine whether instruments are weak (null), with critical values varying between 5.07 and 31.50 (weak identification test) or whether the estimated equation is under-identified (null) with p-value reported (under-identification test); Arellano-Bond for AR(1) to AR(3) (p-value) test for no autocorrelation (null).
Instruments used in all GMM equations are: i_{t-2}, and, lags *t-1* and *t-2* of real potential GDP, monetary base and monetary aggregate M2 all in logs.

Table 5 - Estimated short-run and long-run effects of Fed's asset purchase programs on the long-term interest rate (basis points, per unit increase in the respective qe ratio)

	Short-run effect	**Long-run effect**
qe_1	-53	-298
qe_2	-43	-246
qe_3	-15	-118

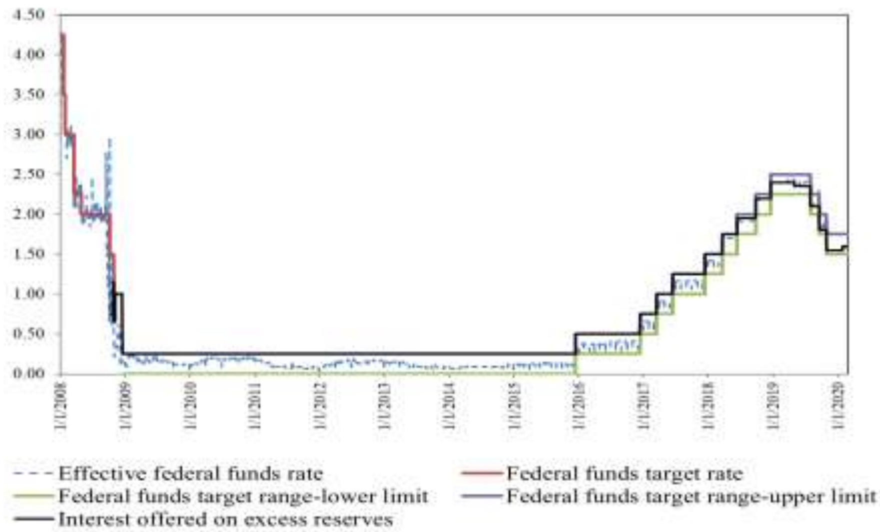
Table 6 – Estimated total effect of Fed's asset purchase programs on the 10-year Treasury yield or term premium across different studies

Study	Estimated total decline	Time period
Ihrig et al. (2018)	100 bps	2008Q4-2015Q4
Bonis et al. (2017)	100 bps 85 bps 24 bps	By end-2016 By end-2017 After full balance-sheet normalization
Li and Wei (2016)	150 bps	LSAP1, LSAP2, MEP
Swanson (2015)	7.5 bps per $300 bn surprise change in LSAP program	2009-2015
Gagnon et al. (2011)	4.4 or 6.4 bps term premium decline for 1-percent-of-GDP decline in long-term debt supply	Short-run effect
	6.9 or 9.8 bps bond yield decline	Short-run effect
	4.2 or 6.2 bps term premium decline	Long-run effect

Table 7 – Estimated total effect of Fed's asset purchase programs on the long-term interest rate during different phases of policy implementation (basis points)

	Balance sheet expansion 2008Q4-2014Q3		**Reinvestments only 2014Q4-2017Q3**		**Balance sheet normalization 2017Q4-2019Q3**	
	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run
qe_1	-69	-386	9	52	15	85
qe_2	-88	-498	4	24	10	57
qe_3	-41	-319	4	33	8	64

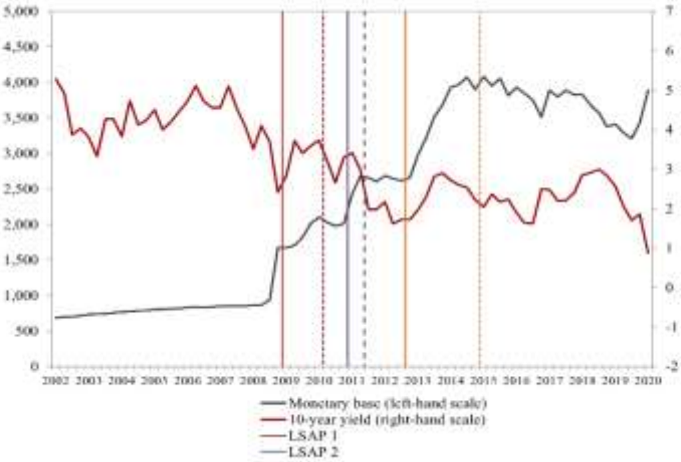
Figure 1: Adjustment of FED’s monetary policy rates and of effective federal funds rate (%)



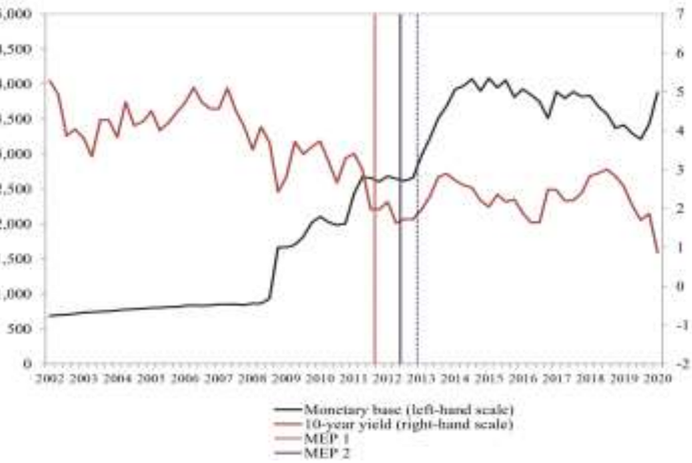
Source: Board of Governors of the Federal Reserve System.

Figure 2: Monetary base (bn $), US 10-year Treasury bond yield (%) and Federal Reserve's asset purchase programs

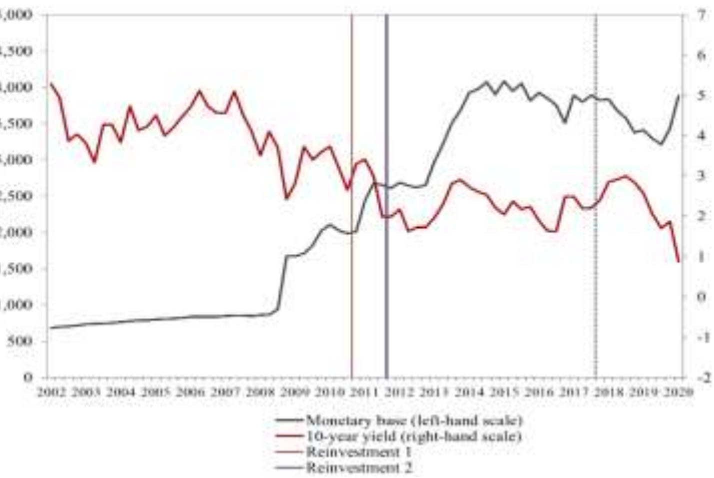
2A. Large-scale asset purchase programs



2B. Maturity extension programs

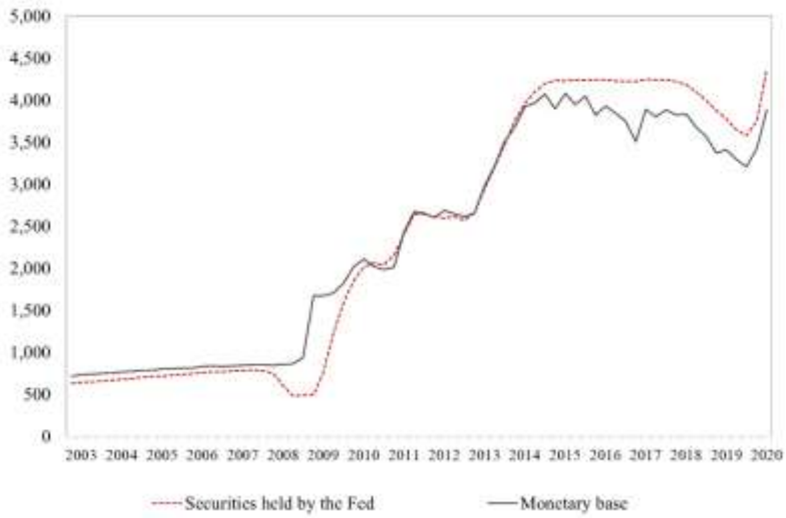


2C. Reinvestment programs



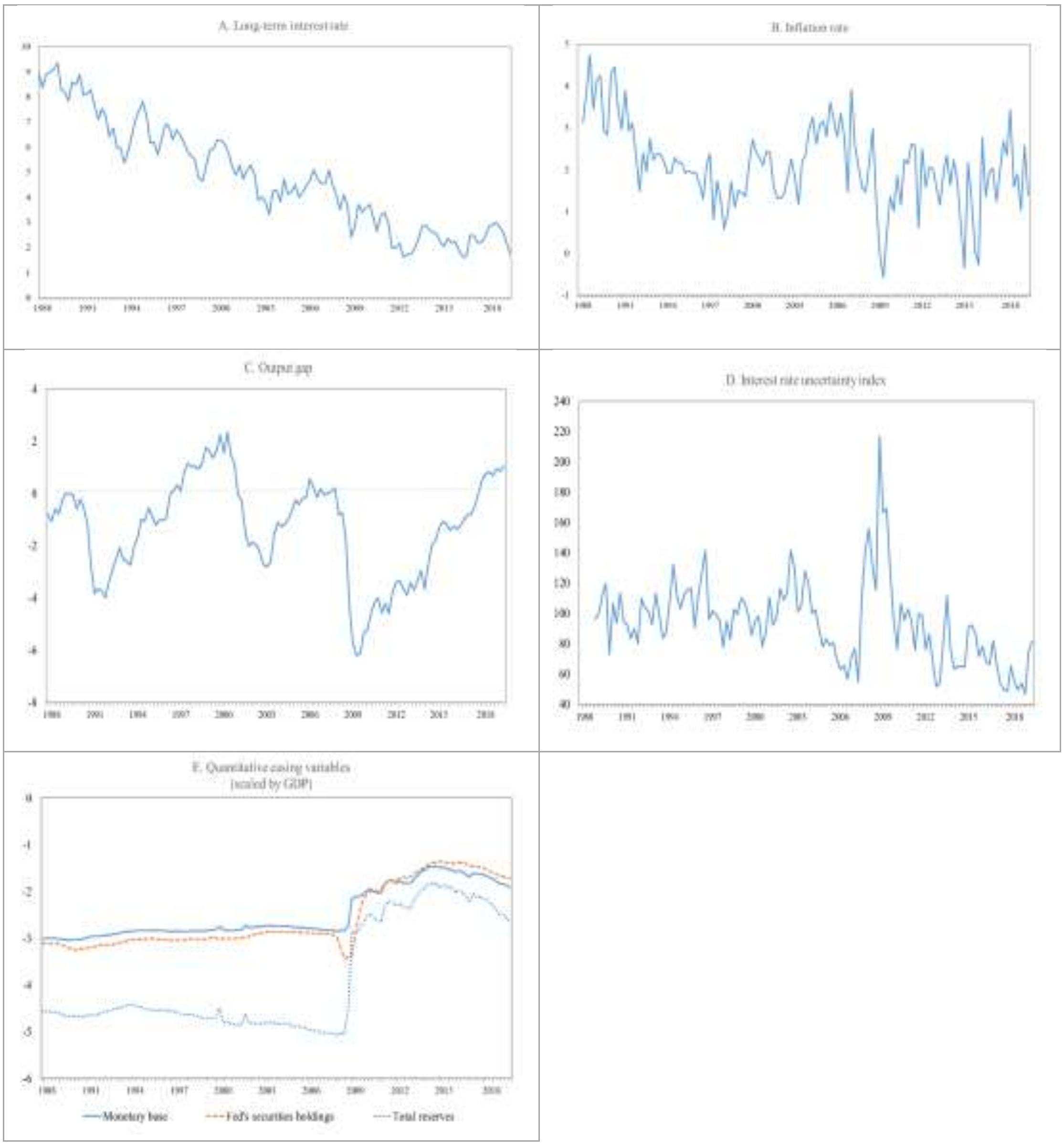
Source: Board of Governors of the Federal Reserve System.
Note: The solid lines represent the start and the dotted lines the end of each program.

Figure 3: Monetary base and Fed's securities holdings (bn $)



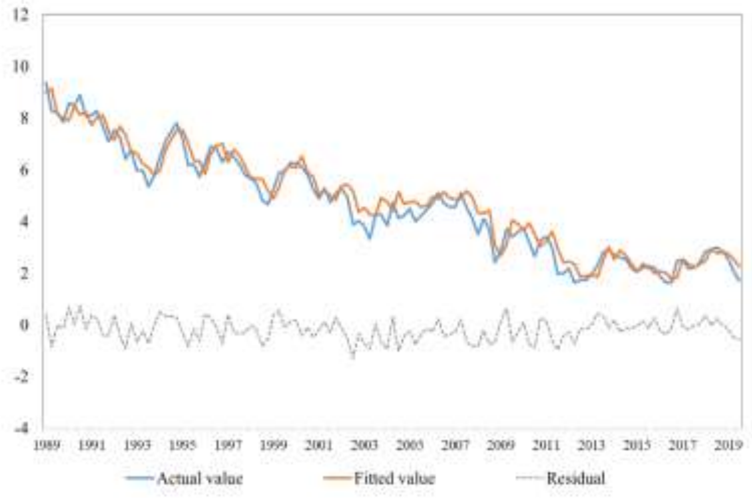
Source: Board of Governors of the Federal Reserve System.
Note: Securities held by the Fed include agency debt, agency MBS and Treasury securities holdings.

Figure 4: Variables used in the empirical analysis



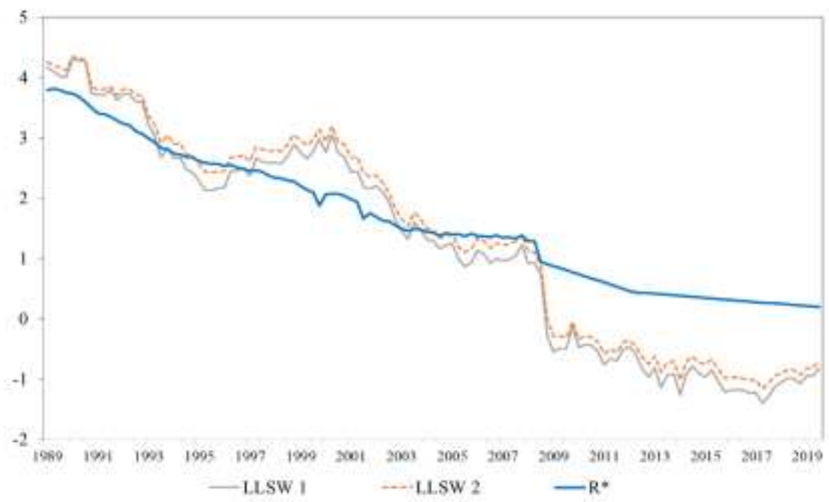
Sources: Board of Governors of the Federal Reserve System, US Bureau of Economic Analysis, US Congressional Budget Office, Thomson Reuters Datastream.

Figure 5: 10-year US Treasury bond yield (%)



Source: Board of Governors of the Federal Reserve System and own estimates.

Figure 6: Estimates of the natural rate of interest (%)



Source: López-Salido et al. (2020) and own estimates.

Notes: LLSW 1 and LLSW 2: López-Salido et al. (2020) estimates; both estimates are based on Blanchard et al. (2015) long-run survey measure of inflation expectations and on (i) Holston et al. (2017) and (ii) the Livingston survey measure of short-run inflation expectations, respectively. R* : own estimate of the long-run equilibrium real interest rate based on eq. (10).

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