DNB Working Paper
No. 691 / August 2020

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DeNederlandscheBank
EUROSYSTEEM

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* Views expressed are those of the authors and do not necessarily reflect official positions of De Nederlandsche Bank.

Working Paper No. 691

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August 2020

A Structural Investigation of Quantitative Easing

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Abstract

Did the Federal Reserves' Quantitative Easing (QE) in the aftermath of the financial crisis have macroeconomic effects? To answer this question, we estimate a large-scale DSGE model over the sample from 1998 until 2020, including data of the Fed's balance sheet. We allow for QE to affect the economy via multiple channels that arise from several financial frictions. Our nonlinear Bayesian likelihood approach fully accounts for the zero lower bound on nominal interest rates. We find that QE increased output by about 1.2 percent, reflecting a net increase in investment of nearly 9 percent accompanied by a 0.7 percent drop in aggregate consumption. Both government bond and capital asset purchases effectively improved financing conditions. Especially capital asset purchases significantly facilitated new investment and increased the production capacity. Against the backdrop of a fall in consumption, supply side effects dominated, leading to a disinflationary effect of about 0.25 percent annually.

Keywords: Quantitative Easing, Liquidity Facilities, Zero Lower Bound, Nonlinear Bayesian Estimation
JEL: E63, C63, E58, E32, C62

1 Introduction

The recent outbreak of the COVID-19 virus in Europe and United States has caused severe turmoil on financial markets, last seen during the Global Financial Crisis (GFC) in

[⋆]The views presented are those of the authors and do not reflect the official position of the Deutsche Bundesbank, De Nederlandsche Bank or the Eurosystem. We are grateful to Kenneth Judd, Keith Kuester, Christian Matthes, Alexander Meyer-Gohde, Alexander Richter, Alexander Scheer, Dominik Thaler, Sweder van Wijnbergen, and participants at the 2019 CEPR MMCN Conference, the PASC 19, the 2019 Conference of the Society of Economic Measurement, the Computational Economics and Finance Conference in Ottawa, 2019, the VfS Jahrestagung 2019, the 20th IWH-CIREQ-GW Macroeconometric Workshop and seminars at the Deutsche Bundesbank, De Nederlandsche Bank, the European Central Bank, the University of Bonn and the University of Lund for discussions and helpful comments on the contents of this paper. Part of the research leading to the results in this paper has received financial support from the Alfred P. Sloan Foundation under the grant agreement G-2016-7176 for the Macroeconomic Model Comparison Initiative (MMCI) at the Institute for Monetary and Financial Stability. Gregor Boehl gratefully acknowledges financial support by the DFG under CRC-TR 224 (project C01). The Online Appendix is available under `http://gregorboehl.com/live/qe_bgs.pdf`.
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2007/08. The Federal Reserve (henceforth Fed) responded – then and today – by quickly lowering its policy rate to levels near zero, providing liquidity to financial markets and purchasing assets in large scale. The latter, so the commonly held view, can be seen as a substitute for conventional monetary policy, if the short-term interest rate is constrained by the zero lower bound (ZLB)[1]. Such conclusions are reassuring as developed economies increasingly find themselves in a "new normal" that is characterized by a low natural rate of interest and low inflation, both of which increase the likelihood of future ZLB episodes (Williams, 2016; Kiley, 2018). And indeed, over the past decade, several studies showed that large-scale asset purchases (LSAPs) – the primary policy instrument at the ZLB – were effective in easing financing conditions through compressing term, credit and liquidity premia.[2] Against this backdrop, unconventional monetary policy measures in general, and LSAPs in particular, have become a permanent part of central banks' toolkits.

Despite their prominent role, however, the macroeconomic impact of LSAPs – in particular, their effect on output, inflation and aggregate investment – remains subject of an open debate. The empirical evidence that aims at answering this question is, by and large, limited to evidence from Vector Autoregression models (including, e.g. Kapetanios et al., 2012; Baumeister and Benati, 2013; Gambacorta et al., 2014; Weale and Wieladek, 2016; Boeckx et al., 2017). While some studies, such as Andres et al. (2004); Gertler and Karadi (2011, 2013); Chen et al. (2012) and Carlstrom et al. (2017), develop structural models to study the effects of QE, in none of the studies, these models are estimated over the relevant sample period due to the challenges posed by the ZLB and the resulting nonlinear estimation. As such, a structural investigation of quantitative easing is yet absent.

In this paper, we close this gap by estimating a large-scale DSGE model over the sample from 1998 until 2020 including data of the Fed's balance sheet. Our model incorporates different channels of the aforementioned literature thereby allowing QE to affect the economy via multiple channels. First, three financial frictions ensure limits to arbitrage between short and long-term assets. On the household side, we assume portfolio adjustment costs for patient households and further assume that impatient households are segmented from the market for short-term assets by being restricted to borrowing in long-term private loans as in Chen et al. (2012). On the banks' side, an agency problem creates an endogenous constraint to the bank's net worth by limiting their ability to obtain funds from households. As a result, the balance sheet of the banking sector becomes a critical determinant of the cost of credit. These assumptions give rise to an extranormal term premium on government bonds, and similarly, extranormal credit risk premia on loans and capital claims. Central bank asset purchases compress these risk spreads, thereby easing financing conditions for firms and households in our model. Importantly, through the portfolio rebalancing channel, these risk spreads are compressed even if the specific asset under consideration is itself not purchased (d'Amico et al., 2012).
Specifically, purchases of capital assets directly affect the real economy by increasing

[1] To name a few, see e.g. Hamilton and Wu (2012); Gertler and Karadi (2013); Kiley (2018); Debortoli et al. (2019); Doniger et al. (2019); Bernanke (2020); Sims and Wu (2020a,b)

[2] See e.g. Gagnon et al. (2011); Krishnamurthy and Vissing-Jorgensen (2011); d'Amico et al. (2012); Bauer and Neely (2014); Swanson (2017) for the US, or e.g. Altavilla and Giannone (2017); Altavilla et al. (2019); Eser et al. (2019) for the euro area

investment.[3] Moreover, through the portfolio rebalancing, also risk premia on loans to households fall, thereby stimulating consumption of impatient households. Purchases of government bonds similarly reduce the credit risk premia on capital assets and loans, albeit by to a lesser extent. Ultimately, by purchasing government bonds, the central bank frees up balance sheet capacity of the banks, which can then increase their supply of credit. Finally, central bank liquidity provisions directly affect a bank's supply of credit by easing it's incentive compatibility constraint.

Our nonlinear Bayesian likelihood approach fully accounts for the ZLB on nominal interest rates. In the context of large-scale DSGE models, the solution, filtering and estimation of models with occasionally binding constraints poses a host of computational challenges. In order to overcome these challenges, we use the solution method developed in Boehl (2020b) together with the proposed nonlinear Bayesian filter and smoother. The linearized model is solved with the ZLB as an endogenous occasionally binding constraint. To allow sampling from possibly multi-modal, disjoined and high-dimensional posterior distribution, we apply a tempered version of the differential evolution Monte Carlo Markov Chain method which uses a large number of chains (ter Braak, 2006; ter Braak and Vrugt, 2008). Different to e.g. Chen et al. (2012) or Carlstrom et al. (2017), we do not have to cut the sample before the GFC when the short-term rate reached the ZLB. Instead, our nonlinear Bayesian likelihood approach allows us to structurally assess the effects of QE through the lens of a large-scale DSGE model during a period where the QE measures were taken, but the ZLB was binding. This enables us to take a far more in-depth account of the effects of these programs.

We find that between 2009 to 2015, QE increased output by about 1.2. According to our results, this reflects a net increase in investment of nearly 9 percent, that was accompanied by a 0.7 percent drop in aggregate consumption. Both, government bond and private security purchases were effective in improving borrowing conditions for households and firms. Purchases of capital securities were the most expansionary by significantly facilitating new investment, thereby increasing the productive capacity. Against the backdrop of a fall in aggregate consumption, however, supply side factors dominated which led to a disinflationary effect of about 0.25 percent annually. While emergency liquidity provision measures sharply lowered the credit spread at the onset of the crisis by around 100 basis points, their macroeconomic effects were negligible due to their short-lived nature.

Our finding of disinflationary effects of QE is well-aligned with recent findings on the effects of financial shocks. Specifically, expansionary financial shocks can be disinflationary if supply effects dominate demand effects. Demand effects dominate, for instance, in models of Curdia and Woodford (2010) and Gertler and Karadi (2011). Consistent with prevailing supply effects, Abbate et al. (2016) show that financial shocks that lower firms' funding costs and increase credit growth and stock prices indeed reduce inflation in the short run. Similarly, but using granular micro-data, Gilchrist et al. (2017) show that firms' with binding liquidity constraints increased prices during the GFC, while unconstrained firms lowered them. To rationalize this empirical finding, the authors

[3]Following Gertler and Karadi (2013), we model the Fed's purchases of mortgage backed securities as the central bank buying claims on the productive capital stock. Despite this discrepancy, our model captures the link between the financial and real economy as balance sheet policies of the central bank affect extranormal credit risk and term premia and thereby lending rates.

build a theoretical model where firms price goods above marginal costs in order to hedge against the risk of relying on costly external finance. Relatedly, Boehl and Lieberknecht (2020) show that a binding ZLB constraint can amplify the inflationary tendency of contractionary financial shocks. Quantitative easing, in turn, can be interpreted as such an expansionary financial shock that substantially lowers long-term interest rates. The resulting surge in investment raises the capital stock in our model. Facing a higher production capacity, firms lower the degree of capital utilization which pushes down the associated marginal costs. This mechanism is similar to Acharya et al. (2020), who find that cheap credit to impaired firms has a disinflationary effect by creating excess production capacity. Against this backdrop, our results suggest that aggregate supply channels dominated in determining the response of inflation to LSAPs.

Our finding that QE can have undesirable effects on inflation and consumption challenges a number of recent findings on the conduct of monetary policy. Debortoli et al. (2019) and Sims and Wu (2020a), among others, prominently argue that conventional and unconventional monetary policy are perfect substitutes. Relatedly, Krippner (2013); Wu and Xia (2016) provide shadow rates that are constructed to include the effects of QE into a framework of standard interest rate setting. In contrast to these papers, we document effects of QE that fundamentally differ from those of standard interest rate policy. As such, our results imply that unconventional measures cannot be simply taken to be a substitute for conventional policy. This cautions against the use of shadow rates and from abstracting from the presence of the ZLB.

Our results are robust to different specifications of the household side which affect the channel of QE to consumption. We show this by estimating the representative agent version of the model. In this model vintage, investment increases more in response to a QE shock than in our benchmark model. The resulting increase in the production capacity even further decreases utilization, inducing an even larger fall in inflation and aggregate consumption. In a second vintage, we replace the impatient households by hand-to-mouth consumers inspired by Kaplan et al. (2018). Other than impatient households, hand-to-mouth consumers do not optimize but simply consume their period labor income, which more closely ties consumption to investment. For this model version, aggregate consumption again falls stronger than in our benchmark model, because falling wages dominate any labor income gains from increased labor supply. As the capacity channel that exerts downward pressure on inflation remains unaltered, the inflation response remains consistent with our benchmark model. We also asses the robustness of our results by estimating the Carlstrom et al. (2017) model the more recent data sample. This confirms the drag on consumption to be a robust consequence of QE. In contrast to our benchmark model, demand effects of LSAPs appear to outweigh their supply effects. We take this result with a considerable degree of caution due to several caveats related to the suitability of the CFP model to this exercise. For instance, we find that this model lacks a demand side shock that allows a strict co-movement of consumption and investment.

The rest of the paper is organized as follows. Section 2 presents the core of our large-scale dynamic general equilibrium model. The nonlinear Bayesian estimation methodology is explained in Section 3. Our posterior estimates are discussed in Section 4, together with an empirical analysis of the GFC and its aftermath. Section 5 then presents our main results in the form of counterfactual analysis of the Fed's unconventional monetary policy measures. Subsequently, in Section 6, we show that our results are robust with respect to several model features. Finally, Section 7 concludes.

2 Model

To study the macroeconomic effects of quantitative easing, we build a large-scale New Keynesian model featuring patient and impatient households, banks, firms as well as a fiscal and a monetary authority. Patient households consume, supply labor and save. Their savings can take the form of short-term bank deposits, private securities backed by firm's capital and government bonds, where the latter two are long-term assets and subject to convex portfolio adjustment costs. In turn, impatient households borrow via long-term private loans from banks besides consuming and supplying labor. Similarly to Chen et al. (2012), households are thus split into "savers" and "borrowers". Banks are modeled as in Gertler and Karadi (2013). They collect deposits from patient households, which they lend on to impatient households, intermediate good producers and the government in the form of long-term bonds and loans. A moral hazard problem constrains their leverage, which creates the necessary limits to arbitrage for QE to have an effect on the banks balance sheet.

The production sector consists of three types of firms for reasons of tractability. Intermediate good producers employ labor and capital to produce their goods. Each period, after producing their output, they sell their used capital stock to the capital goods producers. The latter repair it and invest in new capital. At the end of the period, capital is re-sold to the intermediate good producers which use it for production in the next period. Intermediate goods are purchased by retailers which repackage them and sell them with a markup as final goods. Similarly, labor is differentiated by a union with monopoly power that faces nominal rigidities.

The government consumes final goods, collects taxes, and issues long-term government bonds. Monetary policy sets the short-term interest rate according to a Taylor-type rule which is constrained by the ZLB. In line with the literature on estimated DSGE models, our model also includes standard features such as habit formation in consumption, investment adjustment costs, variable capital utilization, nominal rigidities as in Calvo (1983) in both, price and wage setting, as well as price and wage indexation.

We model large-scale asset purchases of treasury bonds and private capital assets to follow exogenous AR(2) processes. This way, we allow for anticipation and stock effects without necessarily having to specify a policy rule for unconventional monetary policy. Arguably, the measures of QE came as much as a surprise to the US economy as the crisis did. At the same time, once in action the future path of these measures was public information. Our outlined setup approximates this structure. Liquidity injections by the central bank to financial intermediaries are also exogenous.

Finally, time is discrete and one period in the model represent one quarter. Below, we will describe the financial sector and the household structure in more detail, while we refer the reader to the Online Appendix for a full description of the model.

2.1 The household structure

The model is populated by two types of households. We assume a continuum of impatient households with mass χ and a continuum of patient households of mass $1-\chi$. In the spirit of Gertler and Karadi (2013), we impose that a constant fraction f of the patient household works as banker, whereas the remaining fraction $1-f$ consists of workers who – like impatient households – supply labor to the intermediate good producers. While workers receive their wage income every period, bankers reinvest their gains in asset holdings of the bank over several periods. Only when a banker (exogenously) exits the banking sector, she contributes to the patient households' income by bringing home the accumulated profits. Perfect consumption insurance within patient households ensures that workers and bankers face the same consumption stream. The expected lifetime utility of any household i is given by

$$U_t = E_0 \sum_{t=0}^{\infty} \beta_i^t \left(\frac{(C_{i,t} - hC_{i,t-1})^{1-\sigma_c} - 1}{1-\sigma_c} \right) exp \left(\frac{\sigma_c - 1}{1+\sigma_l} L_{i,t}^{1+\sigma_l} \right) \tag{1}$$

where parameters β_i, h, σ_c, and σ_l are, respectively, the discount factor, the degree of external habit formation in consumption, the coefficient of relative risk aversion, and a weight on the disutility of labor. The discount factor has a household-specific subscript i, because we assume the discount factor of impatient households β_m to be smaller than the discount factor of patient households, i.e. $\beta_m < \beta_p$. Finally. $C_{i,t}$ and $L_{i,t}$ denote consumption and hours worked of household $i \in \{m, p\}$, respectively.[4]

2.2 Patient households

The patient household earns the real wage, W_t, for her supplied labor, $L_{p,t}$. She can save in one-period bank deposits, D_t, that pay an interest rate, R_t^d, in government bonds, $B_{h,t}$, that yield an interest rate, R_t^b, and in capital assets $K_{h,t}$ with an associated interest rate, R_t^k. These interest rates are already in real terms, i.e. accounting for inflation. Capital claims, just like government bonds, are modeled as long-term assets. As for all stock variables, we use the end-of-period notation, so that D_t denotes the household's deposits at the end of period t. The return on deposits, $R_t^d = v_{u,t} R_t$, includes a disturbance term, $v_{u,t}$ which drives a wedge between the risk-free real rate and the return on deposits. We assume $v_{u,t}$ to follow an AR(1) process in logs. Smets and Wouters (2007) label this shock a risk-premium shock which they interpret as variations in the confidence in the banking system. Patient households spend their funds on consumption $C_{p,t}$, and save in new deposits, bonds and capital. Savings in government bonds and capital are, as in e.g. Chen et al. (2012) and Gertler and Karadi (2013), subject to portfolio adjustment costs with adjustment parameter κ, once portfolios exceed a level of $K_{h,t} \geq \bar{K}_h$ and $B_{h,t} \geq \bar{B}_h$, respectively. The budget constraint of patient households, in real terms, reads

$$\begin{aligned} C_{p,t} + \frac{D_t}{R_t^d} + Q_t[K_{h,t} + \frac{1}{2}\kappa(K_{h,t} - \bar{K}_h)^2] + Q_t^b[B_{h,t} + \frac{1}{2}\kappa(B_{h,t} - \bar{B}_h)^2] \\ = D_{t-1} + W_t L_{p,t} + R_t^k Q_{t-1} K_{h,t-1} + R_t^b Q_{t-1}^b B_{h,t-1} - T_t + \mathfrak{P}_t. \end{aligned} \tag{2}$$

T_t denotes lump sum taxes raised by the government to finance government spending, and $\mathfrak{P}_t$ are profits of monopolistic firms and banks that accrue to the patient households. Maximizing (1) subject to the patient household's budget constraint (2) and rearranging

[4]For the ease of notation, we only use subscripts $i \in \{m, p\}$ indicating which type of household is meant if necessarily needed.

the first order conditions yields the well-known Euler equation, a condition for the optimal supply of labor and two no-arbitrage conditions:

$$
\begin{aligned}
1 &= \beta_p E_t \left[\exp\left(\frac{\sigma_c - 1}{1+\sigma_l} (L_{p,t+1}^{1+\sigma_l} - L_{p,t}^{1+\sigma_l}) \right) \left(\frac{C_{p,t+1} - hC_{p,t}}{C_{p,t} - hC_{p,t-1}} \right)^{-\sigma_c} \right] R_t^d, && (3) \\
W_t^h &= (C_{p,t} - hC_{p,t-1}) L_{p,t}^{\sigma_l}, && (4) \\
E_t R_{t+1}^k &= R_t^d [1 + \kappa(K_{h,t} - K_h)], && (5) \\
E_t R_{t+1}^b &= R_t^d [1 + \kappa(B_{h,t} - B_h)]. && (6)
\end{aligned}
$$

Ultimately, the no-arbitrage conditions (5) and (6) specify the patient household's optimal holdings of both capital claims and government bonds.

2.3 Impatient households

There is a fraction of χ impatient households which consume, supply labor and borrow long-term private loans from the banks which gives rise to the following budget constraint in real terms

$$
C_{m,t} + R_t^p Q_{t-1}^p B_{m,t-1}^p = W_t L_{m,t} + Q_t^p B_{m,t}^p, \tag{7}
$$

where R_t^P and Q_t^P denote, respectively, the interest rate and price of private loans $B_{m,t}^p$. Price and yield of private loans are related through

$$
R_t^p = \frac{\xi + \kappa_p Q_t^p}{Q_{t-1}^p},
$$

where ξ is the coupon (or redemption) and κ_p denotes the decay factor (Woodford, 1998, 2001). Maximizing (1) subject to the impatient households budget constraint (7) yields, after some rearranging, an Euler equation for the optimal borrowing and a condition for the labor supply of impatient households:

$$
\begin{aligned}
1 &= \beta_m E_t \left[\exp\left(\frac{\sigma_c - 1}{1+\sigma_l} (L_{m,t+1}^{1+\sigma_l} - L_{m,t}^{1+\sigma_l}) \right) \left(\frac{C_{m,t+1} - hC_{m,t}}{C_{m,t} - hC_{m,t-1}} \right)^{-\sigma_c} \right] R_t^p, && (8) \\
W_t^h &= (C_{m,t} - hC_{m,t-1}) L_{m,t}^{\sigma_l}. && (9)
\end{aligned}
$$

2.4 Banks

The banking sector draws on Gertler and Karadi (2013) with the extensions that we outline below. Banks collect deposits D_t from patient households and – together with their own net worth N_t – use these funds to extend loans $B_{b,t}^p$ to impatient households, purchase capital securities from intermediate good producers, $K_{b,t}$, and purchase government bonds $B_{b,t}$. Given these financial operations, the balance sheet of a representative bank then follows as

$$
Q_t K_{b,t} + Q_t^b B_{b,t} + Q_t^p B_{b,t}^p = N_t + D_t + L_t^q, \tag{10}
$$

where L_t^q denotes exogenous emergency liquidity injections by the Federal Reserve. While it can be argued that this might be an ad hoc way of modeling such injections, the provision of central bank liquidity was a very important funding source when interbank market dried up during the height of financial crisis. As such, these operations were essential in preserving market functioning and preventing cascading fire sales which, ultimately, might have led to a credit crunch (Bernanke, 2008; Fleming, 2012). In our model, these liquidity injections directly support bank lending by increasing banks' net worth and easing their financial constraints as shown below. Despite their relatively short duration, these liquidity injections have been sizable, and their effects have not yet been assessed empirically in a structural context. For simplicity, we assume that central bank liquidity is lent at a zero nominal interest rate (i.e. their real rate equals $R_t^L = 1/\Pi_{t+1}$, where Π_t denotes gross inflation). Banks retain their earnings and add it to their current net worth. This gives rise to the following law of motion for the bank's net worth

$$\begin{aligned} N_t = R_t^k Q_{t-1} K_{b,t-1} + R_t^b Q_{t-1}^b B_{b,t-1} + R_t^p Q_{t-1}^p B_{b,t-1}^p \\ -R_{t-1}^d D_{t-1} - R_{t-1}^L L_{t-1}^q. \end{aligned} \tag{11}$$

Note that while the interest rate on deposits raised in period $t-1$ is determined in the same period, the return of assets is risky and only determined after the realization of shocks at the beginning of period t.

Bankers continue accumulating their individual net worth until they (involuntarily) exit the business, which occurs randomly with exogenous probability, $1-\theta$. Conversely, bankers continue their operations with probability θ. Draws from this lottery are i.i.d. and do not depend on the banker's history. When a banker leaves the sector, she adds her terminal wealth, V_t, to the wealth of the patient household she is member of. Therefore, bankers seek to maximize the expected discounted terminal value of their wealth

$$\begin{aligned} V_t &= \max E_t \sum_{i=0}^{\infty} (1-\theta)\theta^i \beta_p^{i+1} \frac{\Lambda_{p,t+1+i}}{\Lambda_{p,t+i}} N_{t+1+i}, \\ &= \max E_t \left[\beta_p \frac{\Lambda_{p,t+1}}{\Lambda_{p,t}} (1-\theta) N_{t+1} + \theta V_{t+1} \right], \end{aligned} \tag{12}$$

where $\Lambda_{p,t}$ denotes the patient household's Lagrangian multiplier with respect to the budget constraint.

Banks operate under perfect competition. If financial intermediation was frictionless, the risk adjusted return on the bank's asset should equal the return on deposits. As in Gertler and Karadi (2013), however, bankers can divert a fraction of their assets and transfer it to their respective households. If they do so, their depositors will withdraw their remaining funds and force the bank into bankruptcy. This moral hazard/costly enforcement problem creates an endogenous limit to the amount of deposits that households are willing to supply. While the latter ensures that bankers earn a strictly positive excess return, it also creates limits to arbitrage, as bankers can not scale-up their balance sheet to arbitrage away any price differences. In order to prevent a banker from diverting a fraction of assets, households keep their deposits at a bank only as long as the bank's continuation value is higher or equal to the amount that the bank can divert. Formally, the latter condition is given by the following incentive compatibility constraint of the bank

$$V_t \geq \lambda_{k,t} Q_t K_{b,t} + \lambda_b Q_t^b B_{b,t} + \lambda_p Q_t^p B_{b,t}^p - \lambda_L L_t^q, \tag{13}$$

where λ_j for $j \in \{k, p, b\}$ denotes the respective fraction of capital claims, government bonds or private loans that the bank can diverted. Following Dedola et al. (2013) and Gelain and Ilbas (2017), we allow $\lambda_{k,t}$ to be time-varying, formally following an AR(1) process in logs with mean λ_k. Ultimately, this shock triggers variations in the divertiblity of capital assets and can be interpreted as variations in the trust depositors have in the quality of banks' capital assets.

In steady state, the λ_j's for $j \in \{k, p, b\}$ determine – together with other estimated parameters such as the discount factor of patient households, β_p, and the trend growth rate, γ – the returns on capital claims and government bonds, R^k and R^b, as well as the private loan rate R^p. We set the prior mean of the relevant parameters such that the respective excess returns over the deposit rate are based on data for the US treasury rate, Gilchrist and Zakrajšek (2012) corporate spread and mortgages rates for private households. This results, a priori, in $\lambda_b < \lambda_p < \lambda_k$, which intuitively can be motivated by the fact that, in general, the collateral value of government bonds is higher than that of mortgage loans and capital claims.[5] The reason is that treasury bonds enjoy higher credit ratings and are subject to less liquidity risks than mortgage loans or capital claims. Finally, the last term in the incentive constraint is due to the assumption that liquidity injections serve to relax the incentive constraint of banks.

To solve the bank problem, let an initial guess of the value function be of the form

$$V_t = \nu_{k,t} Q_t K_{b,t} + \nu_{b,t} Q_t^b B_{b,t} + \nu_{p,t} Q_t^p B_{b,t}^p + \nu_{n,t} N_t + \nu_{L,t} L_t^q, \tag{14}$$

where $\nu_{k,t}, \nu_{b,t}, \nu_{p,t}, \nu_{d,t}$, and $\nu_{L,t}$ are time-varying coefficients. Maximizing (14) with respect to $K_{b,t}, B_{b,t}$ and $B_{b,t}^p$ subject to (13) yields the following first order conditions for capital claims, governments bonds, private loans, and μ_t, the Lagrangian multiplier on the incentive compatibility constraint

$$\nu_{k,t} = \lambda_{k,t} \frac{\mu_t}{1+\mu_t}, \tag{15}$$

$$\nu_{b,t} = \lambda_b \frac{\mu_t}{1+\mu_t}, \tag{16}$$

$$\nu_{p,t} = \lambda_p \frac{\mu_t}{1+\mu_t}, \tag{17}$$

$$\nu_{n,t} N_t + \nu_{L,t} L_t^q = (\lambda_{k,t} - \nu_{k,t}) Q_t K_{b,t} + (\lambda_b - \nu_{b,t}) Q_t^b B_{b,t} + (\lambda_p - \nu_{p,t}) Q_t^p B_{b,t}^p. \tag{18}$$

Given that the incentive compatibility constraint binds[6], we can rewrite this last equation as

$$Q_t K_{b,t} = \frac{\nu_{b,t} - \lambda_b}{\lambda_{k,t} - \nu_{k,t}} Q_t^b B_{b,t} + \frac{\nu_{p,t} - \lambda_p}{\lambda_{k,t} - \nu_{k,t}} Q_t^p B_{b,t}^p + \frac{\nu_{L,t} + \lambda_L}{\lambda_{k,t} - \nu_{kt}} L_t^q + \frac{\nu_{n,t}}{\lambda_{k,t} - \nu_{k,t}} N_t. \tag{19}$$

Intuitively, (19) states that banks' demand for capital claims decreases in λ_j for $j \in \{k, p, b\}$, which regulate the tightness of the incentive constraint with respect to capital claims, mortgage loans over government bonds. Central bank liquidity injections L_t^q, on

[5]In a similar vein, Meeks et al. (2017) use the same approach to distinguish between the collateral values of loans and asset-backed securities.

[6]The constraint binds in the neighborhood of the steady state. For convenience, we make the assumption that it is binding throughout all experiments.

other hand, support the demand for capital claims.

Substituting the demand for capital claims into (14), and combining the result with (15) one can write the terminal value of the banker as a function of its net worth

$$V_t = (1+\mu_t)\nu_{nt}N_t + [(1+\mu_t)\nu_{L,t} + \mu_t\lambda_L]L_t^q \tag{20}$$

A higher continuation value, V_t, is associated with a higher shadow value of holding an additional marginal unit of assets, or put differently, with a higher shadow value of marginally relaxing the incentive compatibility constraint. Then, define the bank's stochastic discount factor as

$$\Omega_t \equiv \frac{\Lambda_{p,t}}{\Lambda_{p,t-1}}\big[(1-\theta) + \theta(1+\mu_t)\nu_{n,t}\big], \tag{21}$$

and substitute (20) into the Bellman equation (12). Using the law of motion for net worth (11), one can then write the value function as

$$\begin{aligned} V_t =&\beta_p E_t\Big[\Omega_{t+1}((R^k_{t+1} - R^d_t)Q_t K_{b,t} + (R^b_{t+1} - R^d_t)Q^b_t B_{b,t} \\ &+ (R^p_{t+1} - R^d_t)Q^p_t B^p_{b,t} + (R^d_t - R_{L,t})L^q_t + R^d_t N_t)\Big] \\ &+ \beta_p E_t\left[\frac{\Lambda_{p,t+1}}{\Lambda_{p,t}}\theta[(1+\mu_{t+1})\nu_{L,t+1} + \mu_{t+1}\Lambda_L]L^q_{t+1}\right] \end{aligned}$$

Finally, verifying the initial guess for the value function yields

$$\nu_{k,t} = \beta_p E_t \Omega_{t+1}(R^k_{t+1} - R^d_t), \tag{22}$$

$$\nu_{b,t} = \beta_p E_t \Omega_{t+1}(R^b_{t+1} - R^d_t), \tag{23}$$

$$\nu_{p,t} = \beta_p E_t \Omega_{t+1}(R^p_{t+1} - R^d_t), \tag{24}$$

$$\nu_{n,t} = \beta_p E_t \Omega_{t+1} R^d_t \tag{25}$$

$$\nu_{L,t} = \beta_p E_t\big[\Omega_{t+1}(R^d_t - R^L_t) + \theta\rho_{cbl}\frac{\Lambda_{p,t+1}}{\Lambda_{p,t}}[(1+\mu_{t+1})\nu_{L,t+1} + \mu_{t+1}\lambda_L]\big], \tag{26}$$

where the last equality follows from the fact that L^q_t follows an AR(1) in logs with persistence parameter ρ_{cbl}.

2.5 Monetary policies and the ZLB

In response to the Great Recession, the Federal Reserve cut its policy rate to essentially zero. We model conventional monetary policy as a standard reaction function with the central bank responding to deviations of inflation from it's target, the output gap and its growth rate

$$\frac{R^s_t}{R^n} = \left(\frac{R^s_{t-1}}{R^n}\right)^{\rho}\left[\left(\frac{\Pi_t}{\Pi}\right)^{\phi_\pi}\left(\frac{Y_t}{Y^*_t}\right)^{\phi_y}\left(\Delta\left(\frac{Y_t}{Y^*_t}\right)\right)^{\phi_{dy}}\right]^{1-\rho} v_{r,t}, \tag{27}$$

with the ZLB constraint

$$R^n_t = \max\left\{\bar{R}, R^s_t\right\}, \tag{28}$$

where we refer to the unconstrained nominal rate R_t^s as the notional (or shadow) rate. Y_t^* denotes the potential output and $\Delta\left(\frac{Y_t}{Y_t^*}\right)$ denotes the growth in the output gap. The parameter ρ_R expresses an interest rate smoothing motive by the central bank over the notional rate and ϕ_π, ϕ_y and ϕ_{dy} are feedback coefficients. The max-operator in (28) reflects the zero lower bound (ZLB) on the nominal interest rate R_t^n, which we take into account in our estimation procedure. For this purpose, $\bar{R}$ denotes the exact level at which the ZLB binds.[7] When the economy is away from the ZLB, the stochastic process $v_{r,t}$ – which follows an AR(1) in logs – represents a regular interest rate shock. However, when the nominal interest rate is zero, $v_{r,t}$ may not directly affect the level of the nominal interest rate. Instead, $v_{r,t}$ affects the expected path of the notional rate, first through it's own persistence and, second, through the persistence in the notional rate, and therefore alter the expected duration of the lower bound spell. At the ZLB, it can hence be viewed as a forward guidance shock.

At the onset of the Financial crisis, the Federal Reserve injected large amounts of liquidity into the financial sector which is known as credit easing. We capture these emergency liquidity injections with an exogenous variable that eases banks' incentive compatibility constraint (13) and thereby stimulates lending. In our estimation, we feed the time series data on these liquidity injections into the model and assume that the associated process follow AR(1) process. That is, formally

$$\tilde{L}_t = \rho_{cbl}\tilde{L}_{t-1} + \epsilon_{CBL,t}, \tag{29}$$

where $\tilde{L} \equiv \frac{L_t^q}{P_t Y_t}$ denotes central bank liquidity as percentage of GDP.

When the policy rate hit the ZLB in December 2008, the Federal Reserve further started its large scale asset purchase program, under which it purchased different debt instruments in order to suppress credit and term premia. In our analysis, we divide these purchases into private (capital) security purchases and government bond purchases, both which we assume to follow an AR(2) process in logs.

$$\tilde{K}_{cb,t} = \rho_{k,1}\tilde{K}_{cb,t-1} + \rho_{k,2}\tilde{K}_{cb,t-2} + \epsilon_{QEK,t}, \tag{30}$$

$$\tilde{B}_{cb,t} = \rho_{b,1}\tilde{B}_{cb,t-1} + \rho_{b,2}\tilde{B}_{cb,t-2} + \epsilon_{QEB,t}. \tag{31}$$

Similar to the liquidity injections, $\tilde{K}$ and $\tilde{B}$ denote, respectively, the central banks capital claim and government bond purchases as a fraction of GDP. The advantage of an AR(2) process is that it can capture the hump-shaped response of the asset purchases, thereby also ensuring anticipation or stock effects at the moment the announcement was made.

3 Estimation and Methodology

The fact that our sample includes a long episode where the ZLB binds poses a host of technical challenges. These are related to the solution, filtering and estimation of the model in the presence of an occasionally binding constraint (OBC). While solution methods for models with OBCs exists – as do nonlinear filters – the satisfactory combination

[7] Given that, empirically, the Federal Funds rate remained strictly above zero, we choose $\bar{R}$ to be slightly above one in our estimation. Moreover, due to the fact that the Fed never implemented negative rates, we use the term "zero lower bound" and "effective lower bound" interchangeably.

of both in the context of a large-scale DSGE model is computationally very expensive and was so far deemed impossible. In this section, we first briefly sketch the set of novel methods proposed by Boehl (2020b) that allow us to estimate such high dimensional models in the presence of a binding ZLB. Subsequently, this section describes our choices with regard to the data.

3.1 Solution method

Throughout this paper we apply the solution method for OBCs presented in Boehl (2020b). We refer to the original paper for details. The model is linearized around its steady state balanced growth path and thereby implicitly detrended. Respecting the ZLB, the original model with the variable vector $\mathbf{y}_t$ can be represented as a piecewise one-sided first-order auxiliary model with

$$\mathbf{N}\begin{vmatrix}\mathbf{v}_t\\ \mathbf{w}_{t-1}\end{vmatrix} + \mathbf{h}\max\left\{\mathbf{p}\begin{vmatrix}E_t\mathbf{v}_{t+1}\\ \mathbf{w}_t\end{vmatrix} + \mathbf{m}\begin{vmatrix}\mathbf{v}_t\\ \mathbf{w}_{t-1}\end{vmatrix},\ \bar{r}\right\} = E_t\begin{vmatrix}\mathbf{v}_{t+1}\\ \mathbf{w}_t\end{vmatrix}, \tag{32}$$

where $\begin{vmatrix}\mathbf{v}_t\\ \mathbf{w}_{t-1}\end{vmatrix} = S\begin{vmatrix}\mathbf{y}_t\\ \varepsilon_t\end{vmatrix}$ is an auxiliary representation. $\mathbf{w}_{t-1}$ contains all the (latent) state variables augmented by the current shocks, and $\mathbf{v}_t$ contains all forward looking variables. $\mathbf{N}$ is the system matrix and $\bar{r}$ is the minimum value of the constrained variable r_t (here, the nominal interest rate). The constraint is included with $r_t = \max\left\{\mathbf{p}\begin{vmatrix}E_t\mathbf{v}_{t+1}\\ \mathbf{w}_t\end{vmatrix} + \mathbf{m}\begin{vmatrix}\mathbf{v}_t\\ \mathbf{w}_{t-1}\end{vmatrix},\ \bar{r}\right\}$. The vector $\mathbf{h}$ contains the effects of r_t onto all other variables. Further, denote by the two integer values k and l respectively the expected duration of the ZLB spell and the expected number of periods before the ZLB binds.

It can be shown that the rational expectations solution to (32) for the state s periods ahead, $(\mathbf{v}_{t+s}, \mathbf{w}_{t+s-1})$, can be expressed in terms of $\mathbf{w}_{t-1}$ and the expectations on k and l as

$$L_s(l,k,\mathbf{w}_{t-1}) = \mathbf{N}^{\max\{s-l,0\}}\hat{\mathbf{N}}^{\min\{l,s\}}S(l,k,\mathbf{w}_{t-1}) \tag{33}$$

$$+ (\mathbf{I}-\mathbf{N})^{-1}(\mathbf{I}-\mathbf{N}^{\max\{s-l,0\}})\mathbf{h}\bar{r} \tag{34}$$

$$= \begin{vmatrix}\mathbf{v}_{t+s}\\ \mathbf{w}_{t+s-1}\end{vmatrix}, \tag{35}$$

where $\hat{\mathbf{N}} = (\mathbf{I}-\mathbf{h}\otimes\mathbf{p})^{-1}(\mathbf{N}+\mathbf{h}\otimes\mathbf{m})$ and

$$S(l,k,\mathbf{w}_{t-1}) = \left\{\mathbf{v}_t : \mathbf{Q}\mathbf{N}^k\hat{\mathbf{N}}\begin{vmatrix}\mathbf{v}_t\\ \mathbf{w}_{t-1}\end{vmatrix} = -\mathbf{Q}(\mathbf{I}-\mathbf{N})^{-1}(\mathbf{I}-\mathbf{N}^k)\mathbf{h}\bar{r}\right\}. \tag{36}$$

Here, $\mathbf{Q} = \begin{vmatrix}\mathbf{I} & -\mathbf{\Omega}\end{vmatrix}$ for $\mathbf{v}_t = \mathbf{\Omega}\mathbf{w}_{t-1}$ represents the linear rational expectations solution of the unconstrained system as e.g. given by Blanchard and Kahn (1980) or Klein (2000).

Finding the equilibrium values of (l,k) must be done numerically. One advantage of the above representation is that the simulation of anticipated equilibrium paths can be avoided when iterating over (l,k). The resulting transition function is a nonlinear state-space representation.[8]

[8] We use the implementations of Boehl (2020a,c) which, for the model presented here, will solve for

3.2 Filtering and Estimation Method

Likelihood inference requires a nonlinear Bayesian filter (An and Schorfheide, 2007). Given the high dimensionality of our model, the particle filter is not feasible.[9] To fill this gap, Boehl (2020b) introduces the transposed-ensemble Kalman filter (TEnKF) which is a hybrid of the particle filter and the Kalman filter. For the transition $t-1 \rightarrow t$ an *ensemble* of particles is sampled from the state distribution at $t-1$. Instead of resampling (particle filter), the TEnKF applies statistical linearization to update the state estimate represented by the ensemble to match each new observation vector. This allows to efficiently approximate the distribution of states for large-scale nonlinear systems with only a few hundred particles instead of several million or billion, as with the particle filter, which is computationally advantageous.[10] Boehl (2020b) also proposes a nonlinear path-adjustment smoother (NPAS) for high-dimensional nonlinear models, which we use obtain the smoothed/historic shock innovations.

We sample from the posterior distribution using a tempered version of the differential evolution Monte Carlo Markov chain method (ter Braak, 2006; ter Braak and Vrugt, 2008, DE-MCMC). The DE-MCMC sampler is a subclass of ensemble MCMC methods. Instead of using a single Markov chain (as e.g. the Metropolis algorithm), such ensemble samplers use a large number of chains (as well called *ensemble*). Proposals for each iteration are generated based on the state of the previous ensemble instead of an explicit proposal distribution. The DE-MCMC sampler is hence self-tuning and the ensemble structure make massive parallelization straightforward. This is in particular important as both the simulation and the filtering step are computationally expensive. The combination of DE-MCMC with tempering (similar to Herbst and Schorfheide, 2014) has the advantage that it is very robust to local maxima and odd-shaped or bimodal distributions.[11]

3.3 Data and calibration

In order to quantify the effects of the large scale asset purchases and liquidity injections taken in the aftermath of the Financial Crisis of 2008-09, we estimate our model on data from 1998:I to 2019:IV. Importantly, and different to earlier papers that also attempt to assess the effects of large-scale asset purchases such as Chen et al. (2012) and Carlstrom et al. (2017), we include the ZLB period and data on the Fed's balance sheet in our nonlinear estimation procedure. We find that including the period in which

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the nonlinear state-space representation of about 80.000 particles draws per processor and second.

[9]The *inversion filter* used in Guerrieri and Iacoviello (2017) and discussed in Cuba-Borda et al. (2019) is also not an option as it is not a Bayesian filter and ignores uncertainty on the initial states and the observations. This may not be crucial for small-scale models without endogenous state variables as in Atkinson et al. (2019), but is important given the high dimensionality of our model and our relatively short data sample.

[10]For all estimations and for the numerical analysis, we use an ensemble of 350 particles. For our model, the evaluation of the likelihood for one parameter vector would then take 1-2 seconds on a single CPU.

[11]We initialize the posterior ensemble with 200 draws sampled from the prior distribution. We then use 8 temperature steps with each 200 iterations. Finally, we let the sampler 2500 run iterations, of which we keep the last 500 ensembles. The posterior parameter distribution is hence represented by $500 \times 200 = 10000$ parameter sets.

QE was conducted to be crucial to properly assess the effects of QE.[12] We abstain from using a longer sample, which includes the Great Inflation and its conquest, because the downward trend in the nominal interest rate observed since the 1980s would severely distort the analysis.[13] Stretching the sample further back in time also bears the risk of misspecification given the large amount of parameters we estimate and, concomitantly, a risk of biasing the effects of QE. For this, we chose the sample to adequately capture the current low interest rate environment and potential structural changes in the economy, like a flatter Phillips curve.[14]

We use a total of eleven observables in the estimation. GDP, consumption, investment and wages are all in real terms and calculated as per capita growth rates. We follow Justiniano et al. (2011) and add durable goods consumption into investment. To measure labor supply, we use average weekly hours worked multiplied by the employment level and divided by civilian noninstitutional population to measure the per capita labor supply. Due to artificial dynamics in the civilian noninstitutional population series that arise from irregular updating (Edge et al., 2013), we use a 4-quarter trailing moving average instead. Inflation is measured as the log differences of the GDP deflator. We include the Federal Funds Rate (FFR) and the Gilchrist and Zakrajšek (2012, henceforth GZ) spread as quarterly rates. The latter is an average credit spread on corporate bonds, very similar to Moody's BAA spread, yet considers the entire spectrum of credit ratings from "single D" to "triple A". While the dynamics of both spreads is very similar over our sample (the correlation of quarterly data reaches 0.9), the GZ spread peaks higher during the Financial crisis but remains less elevated thereafter than the BAA spread, both which is preferred by the model.

For the unconventional monetary policies, we use three observables that we feed into the model as exogenous policy shocks. First, we take the total face value of U.S. Treasury securities held by the Federal Reserve divided by nominal GDP as measure for the Fed's government bond purchases. Second, we add the current face value of mortgage-backed obligations held by Federal Reserve to the net portfolio holdings of the Commercial Paper Funding Facility, both as a fraction of nominal GDP, and use it as a measure for purchases of private capital securities. Third, to measure the Fed's emergency liquidity injections in 2008/09, we add – in line with Fleming (2012) – the central bank liquidity swaps, the current face value of federal agency obligations held by Federal Reserve, the term auction credit held by the Federal Reserve and other loans held by the Federal Reserve, all as a fraction of nominal GDP. The latter mainly includes the Asset-backed Commercial Paper Money Market Mutual Fund Liquidity Facility and the Primary Dealer Credit Facility. Figure 1 shows those three time series.

[12]In the Online Appendix, we show that using the pre-crisis sample from 1983:I until 2008:III may severely bias the effects of these measures.

[13]Boehl and Strobel (2020) show that in the estimation of the canonical Smets and Wouters (2007) model on data from 1983-2019, the downwards trend in the nominal rate is reflected by an artificially elevated consumption series that even in the GFC does not drop below steady-state.

[14]There is an extensive literature that documents a fall in the natural rate of interest and trend inflation since the 1980s (see e.g. Laubach and Williams, 2003; Brand et al., 2018, 2020). Similarly, the semi-structural estimates of Laubach and Williams (2003) and Brand et al. (2020) indicate weak relationships between inflation and economic slack, in line with structural estimates of Del Negro et al. (2015) and Kulish et al. (2017). Finally, a similar flattening has been documented for the wage Phillips curve by e.g. Daly and Hobijn (2014).

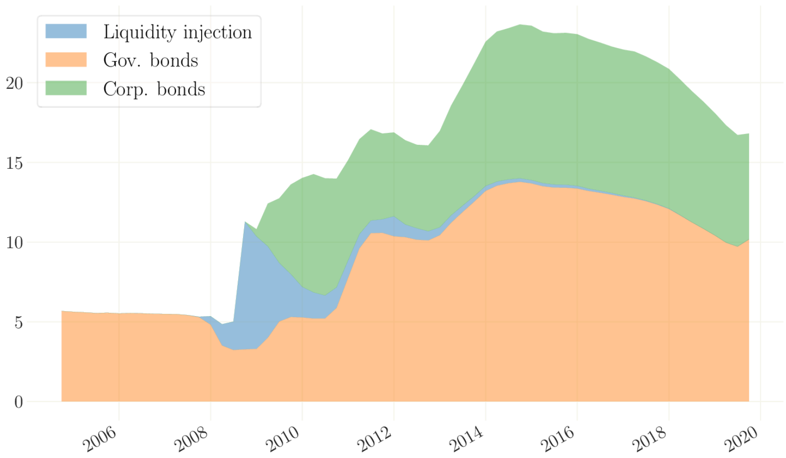

Figure 1: Unconventional monetary policy measures: The Fed's balance sheet expansion.
Note: All variables are in % of GDP. See Appendix A for more details on their construction.

To facilitate the nonlinear filtering, we assume small measurement errors for all variables with a variance that is 0.01 times the variance of the respective series. Since the Federal Funds rate is perfectly observable (though on higher frequency) we divide the measurement error variance here again by 100. Except for labor supply, the data is not demeaned as we assume the non-stationary model follows a balanced growth path that we estimate in line with Smets and Wouters (2007). The measurement equations and a detailed description of the data, as well as its treatment and sources is delegated to Appendix A.

Finally, we fix several parameters prior to estimating the others. In line with Smets and Wouters (2007), we set the depreciation rate to $\delta = 0.025$, the steady state government share in GDP to $G/Y = 0.18$, and the curvature parameters of the Kimball aggregators for prices and wages to $\epsilon_p = \epsilon_w = 10$. The steady state markup in the labor market is set to $\lambda_w = 1.1$. We set the decay factor for both government bonds and private loans to 0.975, which implies an average maturity of 40 quarters. The quarterly coupon/repayment is set to 0.04. Also, we calibrate the empirical lower bound of the nominal interest rate for the U.S. to 0.05% quarterly. Setting it exactly to zero would imply that the ZLB never binds in our estimations, as the observed FFR remained strictly above zero. Our choice therefor maintains that the ZLB is considered binding throughout the period from 2009:Q1 to 2015:Q4. More precisely, it holds that $\bar{r} = -100(\frac{\overline{\pi}}{(\beta\gamma)^{-\sigma_c}} - 1) + 0.05$. Lastly, the Fed's treasury holdings as percentage of GDP have neither been zero nor constant in the years preceding the Financial crisis (see Figure 1). In order to not account these holdings as QE measures, we fix the mean of the central bank's treasury holdings in the measurement equation to $\frac{\overline{B}_{cb}}{Y} = 5.5\%$, and assume this was also the case prior to 2003:I (the first data point observed).

	Prior			Posterior				
	dist.	mean	std	mean	std	mode	5%	95%
σ_c	normal	1.500	0.375	0.908	0.033	0.876	0.854	0.959
σ_l	normal	2.000	0.750	1.160	0.351	1.046	0.581	1.721
β_{tpr}	gamma	0.250	0.100	0.201	0.058	0.186	0.105	0.292
h	beta	0.700	0.100	0.799	0.033	0.804	0.748	0.853
S''	normal	4.000	1.500	5.119	0.754	4.181	3.949	6.370
ι_p	beta	0.500	0.150	0.232	0.067	0.155	0.128	0.343
ι_w	beta	0.500	0.150	0.426	0.118	0.648	0.222	0.617
α	normal	0.300	0.050	0.210	0.012	0.200	0.189	0.229
ζ_p	beta	0.500	0.100	0.870	0.025	0.861	0.828	0.911
ζ_w	beta	0.500	0.100	0.747	0.046	0.728	0.668	0.817
Φ_p	normal	1.250	0.125	1.331	0.071	1.364	1.218	1.445
ψ	beta	0.500	0.150	0.810	0.067	0.841	0.696	0.919
ϕ_π	normal	1.500	0.250	1.323	0.207	1.542	0.962	1.610
ϕ_y	normal	0.125	0.050	0.171	0.022	0.168	0.136	0.207
ϕ_{dy}	normal	0.125	0.050	0.181	0.041	0.239	0.111	0.250
ρ	beta	0.750	0.100	0.829	0.031	0.850	0.777	0.879
$\overline{\gamma}$	normal	0.440	0.050	0.399	0.029	0.414	0.346	0.441
$\overline{\pi}$	gamma	0.625	0.100	0.624	0.058	0.688	0.534	0.718
$\bar{l}$	normal	0.000	2.000	1.246	0.488	0.701	0.416	2.013
κ_τ	gamma	0.300	0.100	0.287	0.081	0.188	0.166	0.425
κ	gamma	2.000	4.000	0.495	1.189	0.132	0.107	0.450
LEV	normal	3.000	1.000	4.312	0.405	4.433	3.635	4.986
θ	beta	0.950	0.050	0.815	0.034	0.747	0.761	0.870
λ_{cbl}	gamma	3.000	3.000	0.229	0.207	0.086	0.001	0.519
χ	beta	0.300	0.100	0.190	0.059	0.133	0.099	0.284
$\overline{termspread}$	gamma	0.500	0.100	0.594	0.106	0.427	0.418	0.773
$\overline{ppremium}$	gamma	0.100	0.030	0.083	0.020	0.110	0.049	0.114
$\overline{spread}$	normal	0.500	0.100	0.428	0.051	0.563	0.340	0.513

Table 1: Estimation results for the baseline model: model parameters

4 The Macroeconomic Context of Quantitative Easing

In this section we present our estimation results and use the estimated benchmark model to give a general account of the US dynamics from 1998 to 2019. The in-depth analysis of the quantitative easing measures is deferred to Section 5.

4.1 Priors and parameter estimates

Our priors and posterior estimates are shown in Tables 1 and 2. All prior distributions are characterized by their mean and standard deviation. The priors for the parameters that pertain to the real economy are chosen in line with Smets and Wouters (2007, henceforth SW).[15] The upper part of Table 1 – the parameters from σ_c to $\bar{l}$ – displays

[15]In contrast to Gust et al. (2017), the computational efficiency of our approach allows us to use the same priors as in SW instead of using tighter prior standard deviations.

	Prior			Posterior				
	dist.	mean	std	mean	std	mode	5%	95%
ρ_r	beta	0.500	0.200	0.566	0.086	0.525	0.421	0.700
ρ_g	beta	0.500	0.200	0.887	0.081	0.944	0.738	0.965
ρ_i	beta	0.500	0.200	0.734	0.048	0.651	0.656	0.810
ρ_z	beta	0.500	0.200	0.951	0.025	0.954	0.915	0.993
ρ_p	beta	0.500	0.200	0.617	0.098	0.624	0.462	0.777
ρ_w	beta	0.500	0.200	0.735	0.070	0.707	0.625	0.852
ρ_u	beta	0.500	0.200	0.896	0.013	0.906	0.873	0.917
ρ_{lk}	beta	0.500	0.200	0.934	0.027	0.936	0.893	0.977
ρ_{cbl}	beta	0.500	0.200	0.762	0.036	0.762	0.704	0.826
$\text{root}_{b,1}$	beta	0.500	0.200	0.903	0.049	0.786	0.835	0.982
$\text{root}_{b,2}$	beta	0.500	0.200	0.880	0.054	0.973	0.794	0.966
$\text{root}_{k,1}$	beta	0.500	0.200	0.901	0.041	0.917	0.833	0.967
$\text{root}_{k,2}$	beta	0.500	0.200	0.926	0.037	0.902	0.870	0.982
μ_p	beta	0.500	0.200	0.450	0.139	0.293	0.195	0.649
μ_w	beta	0.500	0.200	0.517	0.102	0.485	0.345	0.679
ρ_{gz}	normal	0.500	0.250	0.570	0.188	0.463	0.325	0.943
σ_g	inv. gamma	0.100	0.250	0.260	0.029	0.235	0.214	0.307
σ_z	inv. gamma	0.100	0.250	0.345	0.035	0.313	0.282	0.395
σ_r	inv. gamma	0.100	0.250	0.147	0.031	0.164	0.096	0.194
σ_i	inv. gamma	0.100	0.250	0.610	0.086	0.766	0.485	0.760
σ_p	inv. gamma	0.100	0.250	0.235	0.070	0.190	0.125	0.341
σ_w	inv. gamma	0.100	0.250	0.691	0.074	0.687	0.570	0.807
σ_u	inv. gamma	0.100	0.250	0.482	0.086	0.454	0.339	0.617
σ_{lk}	inv. gamma	0.100	0.250	0.272	0.040	0.244	0.208	0.339
σ_{cbl}	inv. gamma	0.100	0.250	0.956	0.084	0.966	0.816	1.090
σ_{qeb}	inv. gamma	0.100	0.250	0.197	0.014	0.186	0.175	0.220
σ_{qek}	inv. gamma	0.100	0.250	0.176	0.015	0.183	0.152	0.198

Table 2: Estimation results for the baseline model: shock processes

the estimates of the parameters inherited from the SW backbone of our model. We compare the posterior estimates for these parameters, among others, to those of Boehl and Strobel (2020, henceforth BS), who estimate the SW model (and extensions) using the same methodology and sample.[16] This comparison seems to be more obvious than the comparison with the results of Kulish et al. (2017), who use a different methodology on a longer data sample. The bottom part of Table 1 contains the new parameters for the financial sector, which are central for the transmission of the large-scale asset purchases. We discuss these parameters mainly in Section 6.1.

Our estimates of the parameters inherited from SW are much aligned with those from BS. The finding that intertemporal elasticity of substitution, σ_c, is close to unity (and well below the prior mean) is widely shared in the literature (see e.g. Smets and Wouters, 2007; Gelain and Ilbas, 2017; Kulish et al., 2017; Boehl and Strobel, 2020). The posterior mean of β_{tpr}, the time preference rate, is close to the estimates by SW, BS, and others.

[16]For convenience, their posterior estimates of the Smets and Wouters (2007) model for the sample until 2020 are repeated in the Online Appendix.

Similarly, BS also find a very high degree of habit formation in their re-estimation of the SW model on the crisis sample (0.833 in BS vs. 0.799 here) as well as substantial investment adjustment costs ($S'' = 5.287$ in BS vs 5.119 here). Both the price and wage Phillips Curves are estimated to be quite flat, with an estimated price Calvo parameter of $\zeta_p = 0.87$ in line with BS and Kulish et al. (2017). Similarly, values for wage and price indexation ι_p and ι_w, as well as the the fixed cost parameter, Φ_p are in a standard range, albeit notably higher than e.g. SW due to the more recent sample. The estimated feedback coefficients of the policy rule as well as the interest rate smoothing parameter, ρ, match the estimates in BS.

We follow Kulish et al. (2017) and BS in the choice of our prior for the common trend $\overline{\gamma}$ and opt for a tighter prior of this parameter than in SW. Arguably, the economy deviated strongly and persistently from its steady state during the Great Recession. In order to dampen the data's pull of the parameter down to the sample mean, we therefore prefer the tight prior as well. This circumvents unrealistically low estimates of the trend growth rate which would imply implausibly high levels of consumption and output after 2008. Our estimates of $\bar{l}$ and mean inflation, $\overline{\pi}$ are in line with BS.[17] The impulse response functions in Figure 6 in Section 5 illustrates that our choice of priors is quite agnostic to the effects of QE, while slightly biased towards the conventional view in which asset purchases induce a similar stimulus as regular interest rate shocks.[18]

For the non-SW part of our model, we estimate the steady state leverage of financial intermediaries, LEV, their survival rate θ, the sensitivity of the incentive constraint to liquidity injections λ_{CBL}, and the feedback coefficient for government debt in the tax rule, κ_{τ}. Additionally, we estimate the AR(2) shock processes for the QE measures, which are identified independently of the model choice. For the prior of LEV we choose a normal distribution centered around 3, and with a standard deviation of 1. Intuitively, a high leverage LEV implies a high initial vulnerability of the financial system to shocks that affect its asset prices or funding costs. Conversely, it also implies that the small steady state net worth that is associated with a high leverage will be replenished (reduced) faster by increased (compressed) excess returns on banks' assets such that the financial system reverses more quickly to its original state. Depending on the nature of the shock this can come either with an amplification or an attenuation of the effects on the real economy. As we are not aware of prior estimates of this parameter in the context of a structural model, we opt for choosing a rather wide prior.[19] For θ, we choose a beta distribution for the prior with a mean of 0.95, corresponding to an expected time horizon of the bankers of 5 years. This value is only slightly below the value of 0.975 in Gertler and Karadi (2011), but the standard deviation of 0.05 allows for significant departures from the prior mean. Generally, a higher θ is associated with a higher stochastic discount factor of financial intermediaries and therefore shapes the persistence of the effects of QE

[17]Note that $\overline{\pi}$ not only is the constant in the measurement equation for inflation, but also the Fed's inflation target and the long-run trend in inflation. We, however, refrain from setting the prior value to 2% p.a. because we assume that the original SW prior better reflects the long-run trend while still being flexible enough to allow for lower estimates if necessary. Moreover, note that the Fed targets headline PCE inflation while, in the estimation, we use GDP deflator consistent with the one-good economy structure of our model.

[18]Additional impulse responses are provided in the Online Appendix.

[19]Villa (2016) estimates a version of the model by Gertler and Karadi (2011) on US data, but calibrates LEV and θ to fixed values.

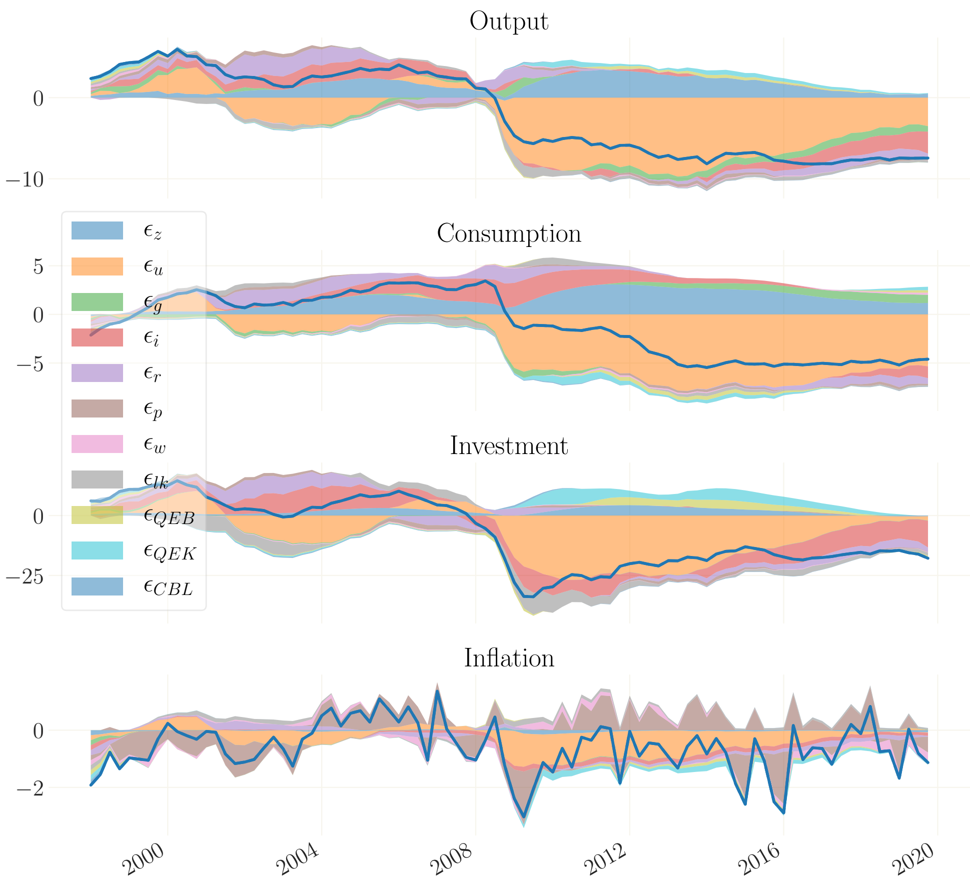

Figure 2: Estimated baseline model. Decomposition of the smoothed states into the contribution of the different shocks.
Note: Means over 1000 simulations drawn from the posterior. The contribution of each shock is normalized and calculated as in Boehl and Strobel (2020). Annual measures where applicable.

shocks. Our estimations however suggest that the data favors large values for *LEV* and a relatively small θ. As we will discuss below, both values point towards rather smaller effects of the QE measures. For λ_{CBL} we set a wide prior around a mean of 3. The shape and width of the prior reflect our agnostic approach to the effect of central bank liquidities injections. For $\lambda_{CBL} = 0$, liquidity injections have no effect at all. In fact, the estimate for λ_{CBL} of 0.229 is quite low, allowing only for limited effects of the Fed's liquidity provision program.

4.2 A decomposition of the dynamics

Figures 2 and 3 show the historical decompositions of a selection of smoothed states into the contributions of the different shocks. The effect of each shock is normalized as suggested by Boehl and Strobel (2020). This means that each shock reflects the exact

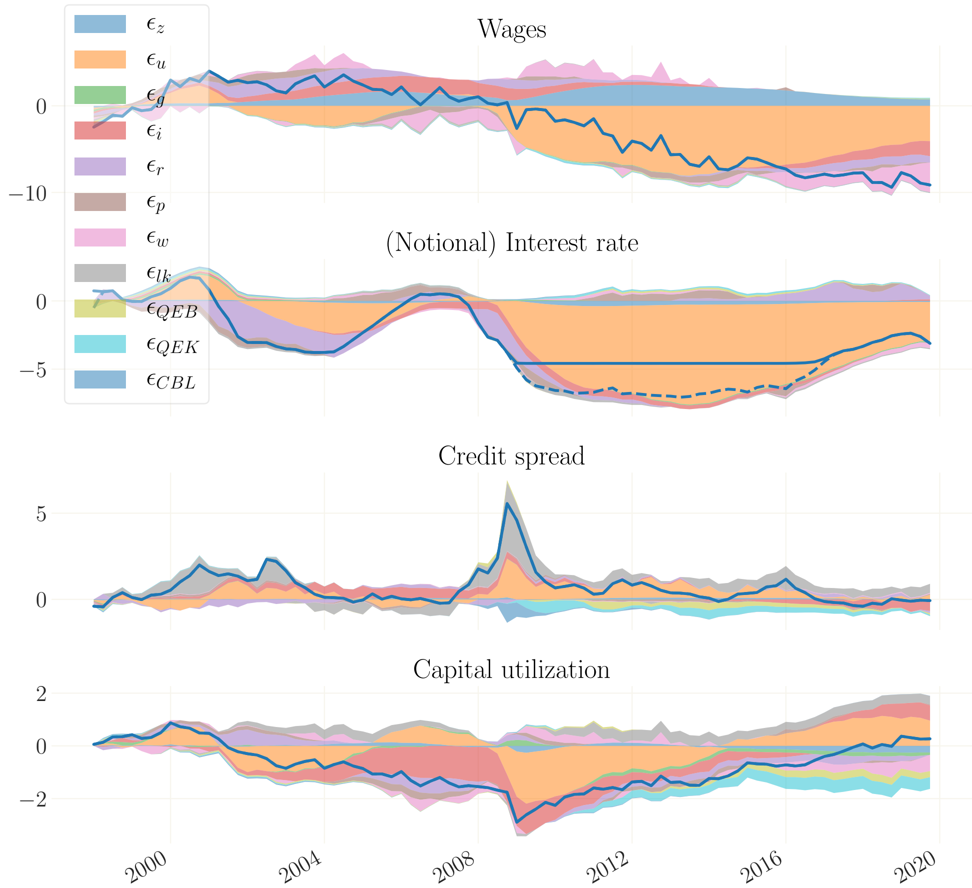

Figure 3: Estimated baseline model. Decomposition of the smoothed states into the contribution of the different shocks.
Note: Means over 1000 simulations drawn from the posterior. The contribution of each shock is normalized and calculated as in Boehl and Strobel (2020). Annual measures where applicable.

contribution, independently of any ordering effects that might occur in nonlinear models. The overall picture of the historical decomposition points towards variations in the risk premium shock, ϵ_t^u, as the most important driver of the observables. This financial shock affects banks' funding conditions and has a demand shock type effect on the real economy in our model. Besides its role in the GFC, it was also identified as a main driver in the pre-crisis period by Smets and Wouters (2007). As such, the high risk premium can not only explain the 2008-2009 drop in consumption, but can also account for a large share of the fall in investment. Ultimately, the lasting effect of an elevated risk premium resonates in a high estimate of ρ_u of 0.896. The plunge in investment is further supported by a fall in the efficiency of investment, ϵ_t^i. To our surprise, the other financial shock ϵ_t^{lk} to the divertibility of capital assets, $\lambda_{k,t}$, that we adopted from Dedola et al. (2013), substantially raises the credit spread during the financial crisis but only plays a minor role in driving macroeconomic dynamics.[20]

The finding of a flat Phillips Curve is mirrored in the dynamics of inflation. While the risk premium shock persistently depresses price level dynamics, the dip of inflation in 2009 is explained by exogenous movements in the firms' price markup. In fact, this process governs almost all high-frequency movements in inflation. As expected, the technology level z_t is a driver of the low-frequency dynamics, which is reflected in a very high estimate of ρ_z. A similar result holds for the process of government spending, which only plays a secondary role.[21]

The parameters for the exogenous processes of the QE measures are identified independently of the model parameters and are entirely driven by the time series of the central bank's balance sheet that are fed into the estimation. In the next section, we provide an in-depth account of the effects of QE and discuss their impact key macroeconomic variables in more detail.

Finally, note that our estimate of the notional rate differs conceptually from those inferred from affine term structure models, such as Krippner (2013) or Wu and Xia (2016). Our estimate reflects the implications of a Taylor-type policy rule and is not based on information of the cross-section of yields. The estimate thus provides a counterfactual, indicating by how much lower the short-term rate would have been given the levels of inflation and the output gap.[22] As we assume that at the ZLB, the Fed considers the shadow rate for interest rate smoothing rather than the nominal rate, the shadow rate directly enters the model. It thus is an important measure as it drives expectation dynamics. At this point, we also want to highlight that our model matches expected durations at the ZLB from survey data surprisingly well.[23] Importantly – and different from Kulish et al. (2017) – we do neither target these expectation nor feed them in to our estimation procedure. They are instead determined endogenously by our solution method.

5 The Quantitative Effects of QE

In response to the GFC, the Federal Reserve undertook several measures in unprecedented scale to address disruptions on financial markets and later to further ease the monetary stance once the ZLB was reached. Among the first such programs are the Term Auction Facility Program (TAF), the Term Asset-Backed Securities Loan Facility (TALF), as well as the primary dealer and other broker-dealer credit programs, which

[20]We also experimented with various other financial shocks, such as the capital quality shock in Gertler and Karadi (2011).We find that the risk-premium shock together with the investment-specific technology shock, the latter which has also been interpreted as a financial shock (see, e.g. Justiniano et al., 2011; Gust et al., 2017; Kulish et al., 2017), to deliver the most robust results and are preferred in terms of the marginal data density (see the Online Appendix).

[21]In principle, our model additionally allows for forward guidance shocks at the ZLB. However, we find that, in the absence of additional data input such as, e.g., term premia, nonlinear filters do not perform reliably well in identify forward guidance shocks at the ZLB. For a related discussion, see Boehl and Strobel (2020).

[22]Note that this ignores the general equilibrium effect of such lower rates: if rates would have been lower, inflation and output would have been higher, and, in turn, the Federal Funds Rate would have been higher than our shadow rate.

[23]In the Online Appendix, we show the evolution of the expected periods at the ZLB.

were aimed at addressing elevated pressures in short-term funding markets at the height of the financial crisis in 2007/08. We summarize these measures under the umbrella of "emergency liquidity injections".

In order to provide further monetary accommodation, the Federal Reserve turned to programs of large-scale asset purchases. The first of these programs, later dubbed "QE1", lasted from December 2008 to March 2010 and included net purchases of $1.25 trillion in mortgage-backed securities (MBS), $175 billion in agency securities and roughly $300 billion in treasury. After a brief pause, a second round of purchases (called "QE2") in November 2010 involved net-purchases of $600 billion plus reinvestment of the proceeds from the earlier MBS purchases in longer term government Treasury securities. After yet another brief pause, the Fed started what is now known as Operation Twist, a portfolio shift of the size of $600 billion from short and medium-term Treasuries with a maturity up to three years, to long-term Treasuries with maturities of six years and above. Our analysis does not explicitly incorporate the effects of Operation Twist, as our data series of government bonds pools Treasuries of all maturities and hence does not account for effectively sterilized actions. Lastly, QE3 started in September 2012 and lasted until December 2014. It further increased the Fed's balance sheet through net-purchases of $95 billion each months – $45 billion in long-term treasury bonds and $40 billion in MBS.

In this section, we investigate the macroeconomic effects of these liquidity provisions and large-scale asset purchases through the lens of our estimated model. As touched upon in Section 2.4, we assume that liquidity provisions directly affect a bank's supply of credit by easing it's incentive compatibility constraint. MBS and commercial paper purchases under QE1 and government bond purchases under QE2, on the other hand, can be interpreted as central bank intermediation (Gertler and Karadi, 2013). The financial frictions in our model give rise to an extranormal term premium on government bonds, and similarly, extranormal credit risk premia on private loans and capital claims. Central bank asset purchases compress these risk spreads, thereby easing financing conditions for firms and households. Importantly, through the portfolio rebalancing channel, these risk spreads are compressed even if the specific asset under consideration is itself not purchased.

We illustrate by the means of counterfactual experiments how output, inflation and the other key macroeconomic variables would have evolved in the absence of the liquidity injections and LSAP programs. While all these measures have prevented a further contraction in investment and hence output, we find LSAPs to have suppressed aggregate consumption by around 0.7 percentage point. Moreover, by increasing the production capacity, LSAPs created additional downward pressure on prices. Although the latter result may appear counterintuitive at first, we show that (positive) financial shocks can have disinflationary effects if aggregate supply effects dominate the aggregate demand.

5.1 The Effects of the QE Measures

What would have happened to the economy if the Fed did not expand its balance sheet in this unprecedented way? We answer this question by looking at counterfactual experiments in which we isolate the effects of each of the balance sheet policies taken. These counterfactuals are summarized in Figures 4 and 5. The red-dashed line on the left indicates the mean of the respective smoothed observable or state. The right side of each Figure then shows the net contribution of the policy measures by adding one measure at the time.

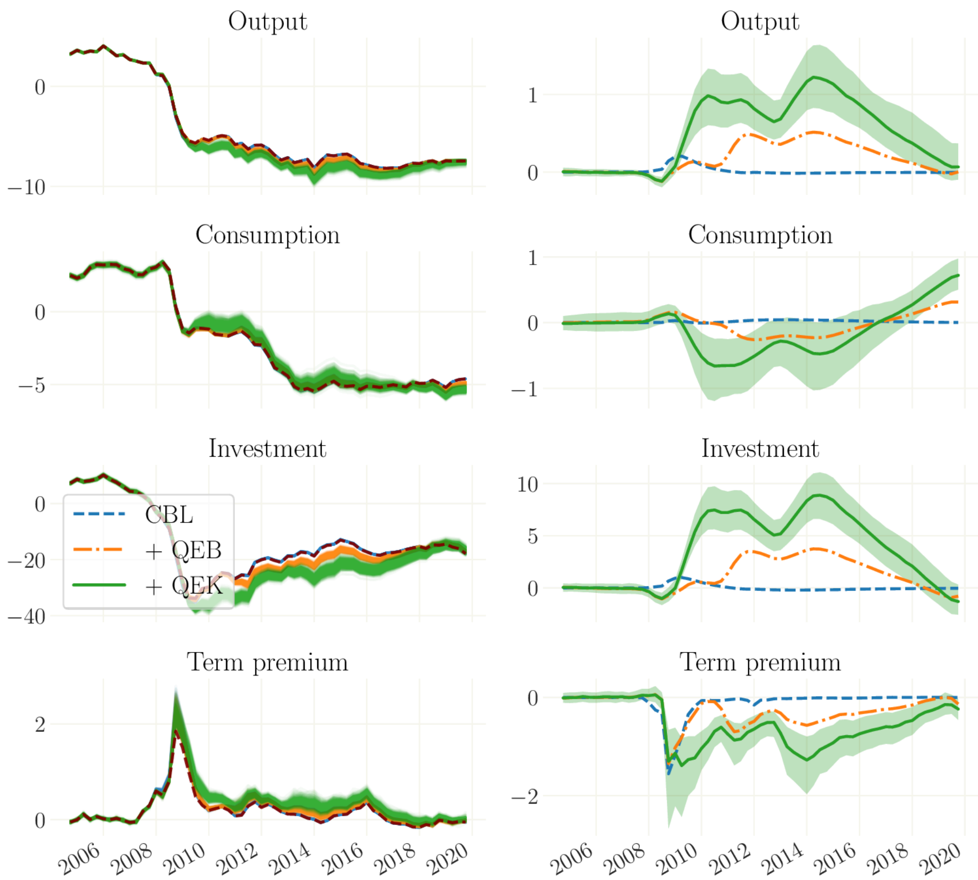

Figure 4: Left: counterfactual simulations without the QE measures. Right: net contribution of each QE measure. Effects in both graphs are cumulative.
Note: Means over 1000 simulations drawn from the posterior. Annualized measures where applicable.

Starting with the liquidity provisions in dashed-blue, denoted CBL in Figures 4 and 5, we observe a sharp fall in the credit spread of around 100 basis points in the beginning of 2009. Despite this large effect on financial conditions, output only increased marginally driven by an increase in consumption of borrowing (i.e. impatient) households and an increase in investment. In the model, liquidity injections trigger a relaxation of the bank's financial constraint which is associated with a broad increase in banks' supply of credit. Their overall macroeconomic effect, however, remained limited: the peak output increase was 0.20%. With the injections reaching around 8% of GDP, their peak output multiplier is only roughly 0.025. Our findings contrast those of Del Negro et al. (2017), who report large effects of liquidity injections on the real economy. One potential reason for this discrepancy is the high persistence of the liquidity shock in their model. Yet Figure 1 suggests and our estimation confirms that the liquidity injections were relatively short-lived, with our posterior mean estimate for persistence parameter $\rho_{cbl} = 0.762$ being substantially smaller than the calibrated value of 0.953 in Del Negro et al. (2017).[24]

We argue, therefore, that the effects of liquidity injections have to be assessed against the backdrop of a smaller magnitude and duration relative to the LSAP programs (as can be seen in Figure 1). In line with the intuition from Equation (19), liquidity injections support bank lending to firms which, in turn, translates into higher investment.[25] The simultaneous fall in the credit spread spills over to the interest rate on private mortgages, which leads to an increase in lending to impatient households, thereby boosting their consumption. However, due to an initial mild fall in inflation the real rate increases, causing a fall in consumption of patient households, which pushes down aggregate consumption in the short run. Total output increases nonetheless, raising labor demand and wages. The latter, in turn supports a pick-up of inflation in the longer term.

In the last quarter of 2008, the Fed started purchasing private securities in order to further ease financing conditions. These holdings reached 9,7% of GDP in 2015 before the Fed slowly started to reduce its position. The securities purchases consisted largely of mortgage-backed securities (MBS), but also included the smaller and more shortly-lived commercial paper funding facility program. Other than the liquidity provisions, LSAPs were very persistent with both estimated roots of each AR(2) process around 0.9. The solid-green line in Figures 4 and 5 indicates that the effects the private capital security purchases were substantial: investment and output were 7% and 0.8% higher, respectively, and the effect persisted over roughly six years before gradually dissipating. In our model, capital securities purchasing basically reflect central bank intermediation (see Gertler and Karadi, 2013), which compressed corporate credit spreads very persistently. The resulting broad appreciation of long-term debt prices via the no-arbitrage conditions bolsters banks' balance sheets and increases their net worth; an effect Brunnermeier and Sannikov (2016) called a "stealth recapitalization" of banks. The increase in banks' net worth, in turn, stimulates lending to impatient households and the government, i.e. the portfolio rebalancing channel (see e.g. Gagnon et al., 2011; d'Amico et al., 2012).

Notwithstanding the positive effects of LSAPs on economic activity, we observe an inconvenient effect of private security purchases on inflation. Our counterfactual suggests that inflation would have been 0.2% higher in the absence of private security purchases, with the 95% credible set even includes a fall of inflation by 0.7%. Although such disinflationary effects may seem counterintuitive at first, the following section will explain the channels of why this result is, in fact, not that surprising, and discusses its robustness together with other empirical literature that support this finding.

At the end of 2010, the Federal Reserve embarked in large-scale purchases of treasury bonds in its second round of QE, which – after a short pause – got extended in September 2012 by the QE3 program. Overall the government bond holdings of the Fed reached close to 14% of GDP. In line with earlier studies, we find purchases of assets that entail some credit risk to be more effective in compressing the excess return on capital assets than purchases of government bonds.[26] The latter translates into a stronger response of

[24]To be precise, Del Negro et al. (2017) model the liquidity shock to be very persistent and with the central bank liquidity policy to respond to the deviations of this persistent shock from its steady state.

[25]In the Online Appendix, we further provide the posterior impulse response functions of central bank liquidity injections.

[26]Krishnamurthy and Vissing-Jorgensen (2011), for instance, find that default risk/default risk premium for corporate bonds fell in response to QE1, thus lowering corporate bond yields. Relatedly,

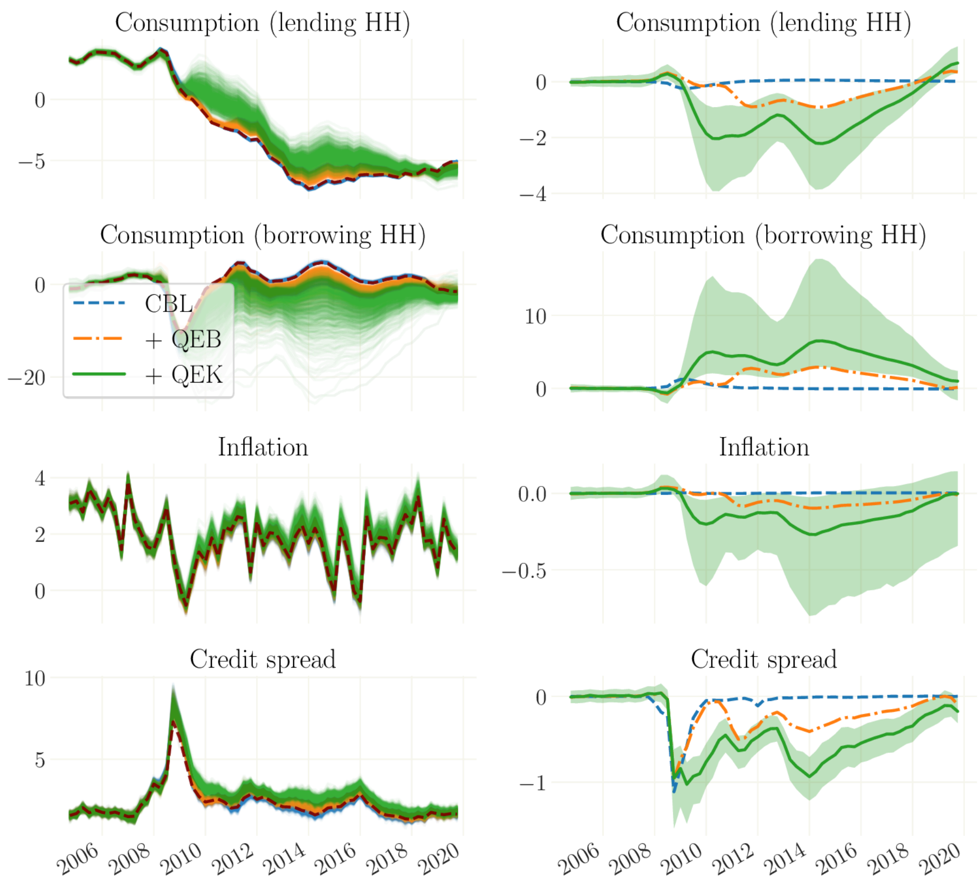

Figure 5: Left: counterfactual simulations without the QE measures. Right: net contribution of each QE measure. Effects in both graphs are cumulative. Measures of spreads and inflation are annualized. *Note:* Means over 1000 simulations drawn from the posterior. Annualized measures where applicable.

investment, consumption of borrowing households and ultimately output. Our counterfactual analysis suggests these treasury purchases to have lifted GDP by 0.5% in 2012 (orange dash-dotted line in Figures 4 and 5). Again, this effect was driven by an increase in investment of more than 4% and consumption of borrowing households of around 3%. The effect on aggregate consumption is, however, more benign, as consumption of savers (i.e. patient households) slightly falls. The reason for the latter is again a mild disinflationary effect of the government bond purchases, which leads to an increase in the real deposit rate. Additionally, the rise in the return on capital increases impatient households' marginal benefits of investing over and above their marginal costs of fore-

Caballero and Farhi (2018) show that central bank purchases of risky assets (in contrast to save government bonds) in a swap for safe assets (central bank reserves) can boost the economy and lower risk premia.

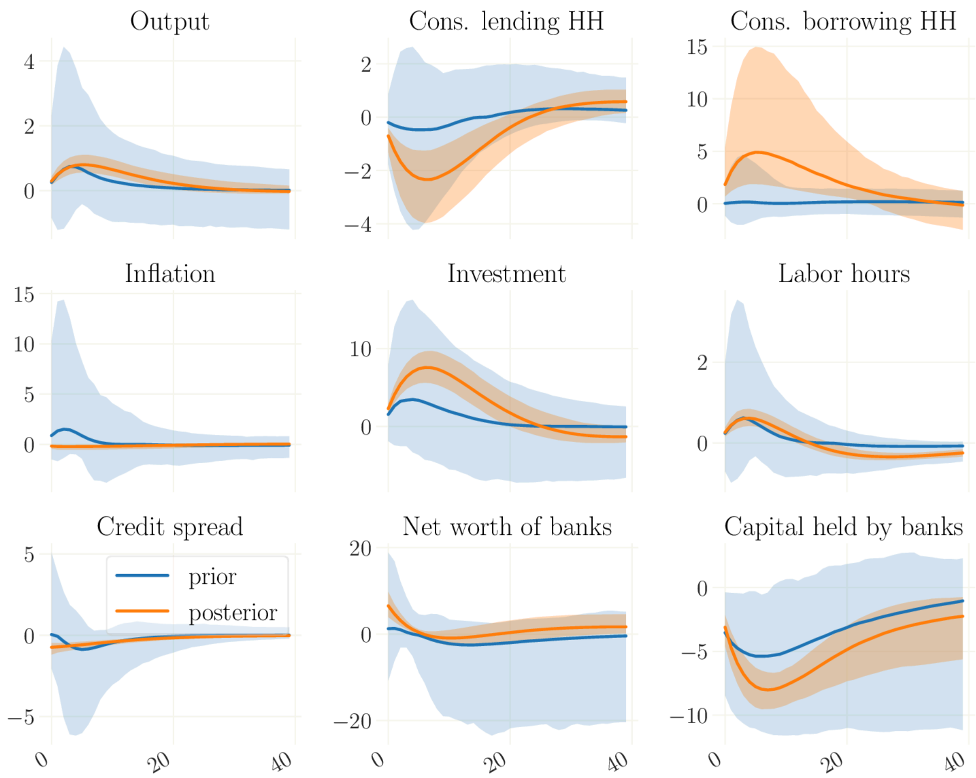

Figure 6: Prior and posterior impulse response functions of a shock to private security purchases. .
Note: Posterior IRFs in orange, with 95% credible set. Posterior sample obtained from 1000 draws from the posterior distribution. Prior IRFs in blue. Solid lines represent the mean. For each draw, the strength of the shock is chosen such that the peak of the corresponding stochastic process matches the peak of the empirical time series. See the Online Appendix for details. The prior sample is obtained from 2000 draws to account for the strong heterogeneity of effects. Prior draws adjusted for high autoregressive coefficients with mean/std of 0.9 and 0.05 because AR-coefficients are identified independently from the model. Annualized measures where applicable.

gone consumption. Contrary, borrowing households see their risk spread decline (via the portfolio rebalancing channel) by more than the fall in inflation, which stimulates their consumption.[27]

5.2 The disinflationary effect of Quantitative Easing

As displayed in Figure 5, we find that the LSAPs had an unpleasant effect on inflation and consumption. This implies that, at a time when inflation was still depressed by the persistent effect of the GFC, the QE measures exerted additional downward pressure on

[27]In line with the consumption response of indebted households in our model, Di Maggio et al. (2020) provide evidence from micro data that QE1 helped some households to refinance their mortgages and to increase their consumption.

the price level. The disinflationary effects are particularly pronounced for the purchases under QE1, which – over the course of the program – induced inflation to drop an additional 0.25% with the maximum effect in the 95% credible set even exceeding 0.7% p.a. While the main goal of QE in the US was to create favorable financing conditions and to stimulate lending[28], our finding of a disinflationary effect of QE is highly policy relevant. Specifically, in the US, LSAPs create a trade-off for policymakers between the stabilization of prices and employment. But the results may be even more important for the Euro Area, where the asset purchase programme (APP) of the ECB was explicitly undertaken to stabilize inflation and inflation expectations at a time when fears of deflation surged.[29]

It is important to note that this result stands in stark contrast to the effects that occur when sampling from the prior distribution. To illustrate this, Figure 6 shows the response functions to an impulse in private security purchases at both our prior and posterior mean. The former suggests a peak effect on inflation of 2%, with the 95% credible set even allowing to peak at 14%. Against this backdrop, we see our posterior result as a strong case for the data to prefer a disinflationary effect of the Fed's Quantitative Easing measures.

To understand this effect, let us recognize that in our model, LSAPs can be interpreted as an expansionary financial shock that loosens liquidity and balance sheet constraints. The response of inflation depends, inter alia, on whether aggregate demand or supply effects dominate. For instance, inflation may rise if demand effects dominate, as is the case in Curdia and Woodford (2010) and Gertler and Karadi (2011). Contrary, if supply side effects dominate, expansionary financial shocks may in fact be disinflationary as lower financing costs may be passed on to prices.

According to our prior predictive analysis, the priors we choose, give an edge to demand side effects on unconventional monetary policy. An easing of borrowing conditions for households and firms stimulates aggregate spending. Higher aggregate demand, in turn, increases factor demand, thereby raising factor prices. Elevated marginal costs are, over time, passed on to consumers in form of higher prices. Higher inflation further lowers real interest rates which amplifies the initial increase in aggregate demand. In fact and to the best of our knowledge, such effects also prevail in all common models of QE, including the original Gertler and Karadi (2013) framework which lends as a blueprint for our benchmark model and its derivatives. As such, QE appears a priori to work similarly to an expansionary monetary policy shock.

Notwithstanding, our estimation favors the dominance of the supply side channels of QE.[30] To formally understand the mechanism in our model, recall that firms use a standard Cobb-Douglas production function of the form $Y_t = F(Z_t, L_t, \bar{K}_t)$, where $\bar{K}_t = U_t K_{t-1}$ is the effective capital in period t. That is, in each period, firms must take their capital stock as given but can decide over the utilization rate U_t. As in Smets

[28] See the Fed's statement from November 25th, 2008.

[29] See, for instance, the ECB's press release from January 2015, which rationalizes the public sector asset purchase programme (PSPP) "*in order to address the risks of a too prolonged period of low inflation.*"

[30] In the Online Appendix, we further show that demand side effects dominate in the response of inflation to a standard monetary policy shock given our benchmark estimation. Despite their diverging implications in consumption and inflation, we further compare the effects of QE measures with those of a conventional monetary policy shock.

and Wouters (2007), the costs for changes in the utilization rate are given by a function $\Psi(U_t)$ that increases proportionally when U_t deviates from its steady-state value. Thus, the marginal product of effective capital, $\widehat{mpk}_t$ depends on the capital utilization rate and can, up to a first-order approximation, be expressed as

$$\widehat{mpk}_t = \frac{\psi}{1-\psi}\hat{u}_t, \tag{37}$$

where $\hat{x}_t$ represents a variable X_t in percentage deviations from its steady state. The parameter ψ depends positively on the elasticity of the capital utilization adjustment cost function and is defined on $(0,1)$. Moreover, since marginal costs $\widehat{mc}_t$ is linked to the marginal factor product, we have

$$\widehat{mc}_t = (1-\alpha)\hat{w}_t - \hat{z}_t + \alpha\frac{\psi}{1-\psi}\hat{u}_t, \tag{38}$$

i.e. marginal costs increase in real wages $\hat{w}_t$ and the rate of capital utilization $\hat{u}_t$ and decrease in total factor productivity, $\hat{z}_t$.

For simplicity, let us picture the purchases of capital assets by the central banks as an exogenous shock on the capital stock (via increased investment). For a given aggregate demand, an increase in the capital stock will mechanically decrease the utilization rate and, correspondingly, the marginal product of effective capital. Holding wages constant, this directly translates into lower marginal costs and, in turn, prices and inflation via the New Keynesian Phillips curve. Additionally, the decrease in consumption by patient households supports a slight decline in wages via the wealth effect on the labor supply. This adds to the downward pressure on inflation.

Importantly, note that this mechanism, and thereby the disinflationary effect of QE, does not hinge on the presence of time-varying capital utilization. In fact, the rise in the capital stock leads to a fall in marginal cost even in the absence of varying capital utilization via an increase in the marginal product of labor.[31]

The notion that a loosening of financial constraints is associated with disinflationary tendencies is quite common in the literature. For instance, Boehl and Lieberknecht (2020) show that at the ZLB, the costs of external financing (i.e. credit spread) can dominate firms' price setting, which results in a flatter Philips curve. Similarly, in models with a cost channel where firms borrow in advance of production to pay wages, as in Van Wijnbergen (1983); Christiano et al. (2005) and Ravenna and Walsh (2006), or capital as in Fiore and Tristani (2013), lower credit spreads (and hence financing costs) are associated with a decrease in firms' marginal costs which is passed on to consumers in the form of lower prices. Consistent with prevailing supply effects, Barth III and Ramey (2001); Chowdhury et al. (2006) and Abbate et al. (2016) find evidence in favor of a cost channel. Abbate et al. (2016), for instance, show that – using a vector autoregression model with sign restrictions – financial shocks that lower firms' funding costs and increase credit growth and stock prices actually reduce inflation in the short run. Similarly, using Italian firm-level data on output prices and interest rates paid on debt, Gaiotti and Secchi (2006) find the cost channel to be proportional to the working capital. A different yet

[31]The Online Appendix also provides a brief exposition of the results for the model without capital utilization.

related channel is proposed by Gilchrist et al. (2017). Using granular micro-data, the authors show that firms' with binding liquidity constraints increased prices during the GFC, while unconstrained firms did lowered them. To rationalize this empirical finding, Gilchrist et al. (2017) build a theoretical model where firms price goods above marginal costs in order to hedge against the risk of relying on costly external finance.

As discussed above, in our model, we identify a *cost channel of QE* that materializes via the capital utilization cost, which decrease following a QE-induced rise in investment. This mechanism is similar to Acharya et al. (2020), who find that cheap credit to impaired firms has a disinflationary effect by creating excess production capacity. Against this backdrop, our results suggest that aggregate supply channels dominated in determining the response of inflation to LSAPs.

6 Robustness

In this section, we first analyze which parameters are the root cause for the disinflationary effects and the fall in consumption resulting from LSAPs in section 6.1. We then show that our main results are also robust to specific model assumption by estimating different model vintages in section 6.2. Lastly, we present the effects of LSAPs through the lens of an estimated version of the model by Carlstrom et al. (2017) and discuss the differences to our benchmark results.

6.1 Model parameters - Inspecting the mechanism

As shown in the previous section, according to (38), the effect of an increase in the utilization rate on marginal costs depends, ceteris paribus, positively on ψ and α. The estimate of α additionally governs the relative weight of the marginal product of capital and wages in the marginal costs. The blue line and shades in Figure 7 show the posterior IRFs to capital asset purchases together with their 95% credible sets. To highlight the effect of the parameter estimates on inflation dynamics, the green lines show the IRFs for the case in which ψ is set to their prior mean. The increased capital stock induced by higher investments leads to a fall in capital utilization, $\hat{u}_t$, and, correspondingly, the marginal product of capital. In addition with the decline in wages this implies a proportional decline in marginal costs and, ultimately, inflation. As can be seen in Figure 7, our estimate of ψ supports a disinflationary effect of the asset purchasing program in our benchmark model. The posterior mean value of ψ is 0.810 with a standard deviation of 0.067 (see Table 1) lies between the estimate of a plain Smets and Wouters (2007) model on the same sample using the same methodology (see the Online Appendix) and the one reported in Kulish et al. (2017). Contrary, for the capital share, our posterior mean estimate of $\alpha = 0.210$ dampens the disinflationary effect compared to a simulation in which α is replaced by its prior mean of 0.3. However, this effect is rather mild. The posterior mean value is notably higher than those from either a plain SW model, those reported by Kulish et al. (2017) and those reported for a selection of models in Boehl and Strobel (2020), which all range between 0.16-0.174.

For the financial sector, we estimate the survival probability of banks, θ, and the steady state leverage ratio, LEV. Figure 7 illustrates the effects of θ on the transmission of central bank capital purchases. The posterior mean estimate of $\theta = 0.815$ lies well below the parameter's prior mean of 0.95. The lower survival probability is associated

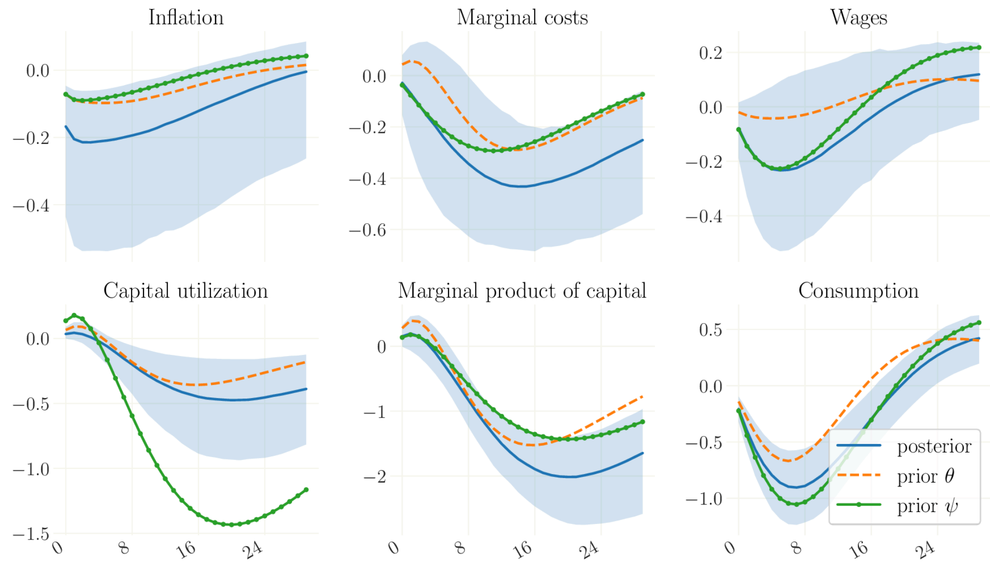

Figure 7: Impulse response functions with respect to a shock of capital securities purchases in blue, sampled from the posterior distribution with 95% credible set. In orange impulse responses at the posterior mean with $\theta = 0.95$. In green impulse responses at the posterior mean with $\psi = 0.5$.
Note: Posterior sample obtained from 1000 draws from the posterior distribution, solid line represent the mean. For each draw, the strength of the shock is chosen such that the peak of the corresponding stochastic process matches the peak of the empirical time series. See the Online Appendix for details. Annualized measures where applicable.

with a smaller share of incumbent bankers in this sectors, whose excess returns are affected by current and past shocks. Therefore, in the model a lower θ somewhat insulates the sector as a whole from the effects of reduced profitability of bank assets. Overall, the impulse to investment is strengthened by a lower survival probability of bankers, and therefore aggregate output as well. The stronger expansion of the capital stock again lowers marginal costs and inflation. Hence, the low estimate of θ supports the disinflationary effects of unconventional monetary policy. The estimate of LEV above its prior mean is associated with a relatively attenuated expansion of investment and output in response to LSAPs. Inflation is, however, barely affected. The attenuation of these shocks associated with a high steady state leverage ratio can be explained by the fact that the compressed excess returns on bank assets quickly undo the gains in net worth triggered by the central banks asset purchases (see Equation (11)). This reduction in the profitability on assets has a stronger effect and causes a faster mean reversions, when the asset position is relatively large compared to the net worth of banks. As the gains in the financial sector are more short-lived, the investment response is attenuated.[32]

[32]Note, that a higher LEV is also associated with an amplification of risk premium shocks, which affect financial intermediates primarily via their funding costs. This is important, as risk premium shocks drive the bulk of the business cycle. Higher leverage ratios can therefore be associated with a deeper recession following the GFC.

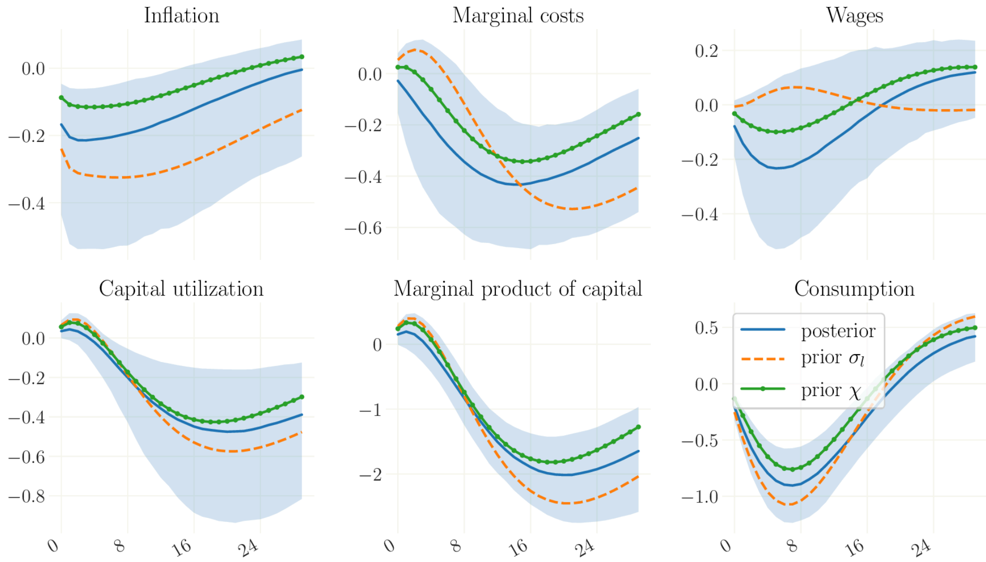

Figure 8: Impulse response functions with respect to a shock of capital securities purchases in blue, sampled from the posterior distribution with 95% credible set. In orange impulse responses at the posterior mean with $\sigma_l = 2$. In green impulse responses at the posterior mean with $\chi = 0.3$.
Note: Posterior sample obtained from 1000 draws from the posterior distribution, solid line represent the mean. For each draw, the strength of the shock is chosen such that the peak of the corresponding stochastic process matches the peak of the empirical time series. See the Online Appendix for details. Annualized measures where applicable.

On the household side, the preference parameters σ_c and σ_l affect the transmission of unconventional monetary policy shocks. Figure 8 compares the IRFs sampled from the posterior with IRFs in which the inverse of the Frisch elasticity, σ_l, is set to its prior mean. Our estimate of σ_l is below its prior mean. The low slope of the labor supply schedule comes with a stronger but more short-lived fall of wages in response to central bank capital asset purchases. This translates to a qualitatively similar pattern in marginal costs and, since inflation is strongly forward looking, is associated with a attenuated decrease in inflation compared to the case, in which σ_l is replaced by its prior mean. As discussed in section 3, a posterior mean estimate of $\sigma_c = 0.908$ is in close proximity to values commonly found in the literature. A high coefficient of relative risk aversion at its prior mean implies a low sensitivity to changes in the real rate and establishes a positive co-movement of household spending and labor hours via the non-separabilities in preferences (see Equations (3) and (8)). In contrast, the posterior value slightly below unity reduces the latter channel and even slightly reverses its effect, such that, in sum, aggregate spending declines. In turn, the fall in consumption causes an expansion of the labor supply schedule and reduces real wages. Consequently, the low estimate of σ_c substantially weakens the demand effect of quantitative easing and supports its disinflationary implications. Importantly, this parameter is well identified, which adds to our argument that the data favors disinflationary effects of LSAPs. Also on the household side of the model, the fraction of impatient households, χ affects the response of consumption, real wages and inflation to unconventional monetary policy measures. We show the counterfactual simulation with χ at its prior mean as well in Figure 8. The households profit from lower funding costs and increase their spending in response to quantitative easing. Our estimate of this parameter is at 0.190 and therefore considerably below its prior mean. For a higher value of χ, the reduction in consumption and inflation is dampened. Notably, given the other parameter estimates, it would require a fraction of borrowing households as high as 0.5 to generate roughly neutral effects of LSAPs on inflation and consumption – a value which is far away from what the data favors.

6.2 Model features

In Gertler and Karadi (2013), the representative household is a "saver", with those savings in form of bank deposits and investments into both, corporate and government bonds. In response to a QE shock (private security or government bond purchases), household consumption only increases to the extent that the real deposit rates falls. The model, however, does not allow QE to directly affect consumption. For this reason, our baseline model features a second type of households, namely the impatient, that can borrow using long-term private mortgages to finance his consumption. This channel is comparable to the one presented in Chen et al. (2012) and allows for a direct impact of loser financing conditions on private consumption. In particular, after a QE shock, impatient households will see their borrowing costs falling, which stimulates their consumption and thereby, possibly, aggregate consumption. As discussed in the previous section, we estimate the fraction of impatient households to equal $\chi = 0.195$.

In order to show that our results do not hinge on this additional channel of QE, we propose two alternative specifications of our benchmark in this section.[33] First, we estimate the representative agent version of our model, which we call the RANK version, by setting the share of impatient households $\chi = 0$. This model vintage does not allow for indebted households and, as a result, QE does not affect household consumption directly, but only to the extent that it affects the real deposit rate. Second, we estimate a model in which we replace the fraction of impatient households with "hand-to-mouth" (H2M) consumers inspired by Kaplan et al. (2018) in the spirit of Campbell and Mankiw (1989, 1991). Neither in this model vintage, denoted H2M, does QE affect consumption directly. Instead, any effects on consumption have to come from the response of labor income (i.e. real wages and/or labor supply) and again the real deposit rate.

Figure 9 repeats the counterfactual analysis of section 5.1 for the RANK model. The overall effects of the UMP measures seem to be consistent even in the absence of the above described channel. Despite a similar increase in investment increases of around 10%, the overall effect on output is more muted, peaking at around 0.5%. The reason for this substantially smaller output effect lies in the twice as large decline in the price level, now reaching on average -0.5%, and the accompanied stronger fall in consumption that weighs on aggregate demand. While most parameter estimates remain, by and large, unchanged, a handful of parameter estimates reflects these dynamics. Specifically, in σ_l falls from 1.231 in the benchmark model to 0.654 in order to rationalize the stronger

[33]See the Online Appendix for the posterior estimates, the impulse responses and historical shock decompositions of these model vintages, respectively.

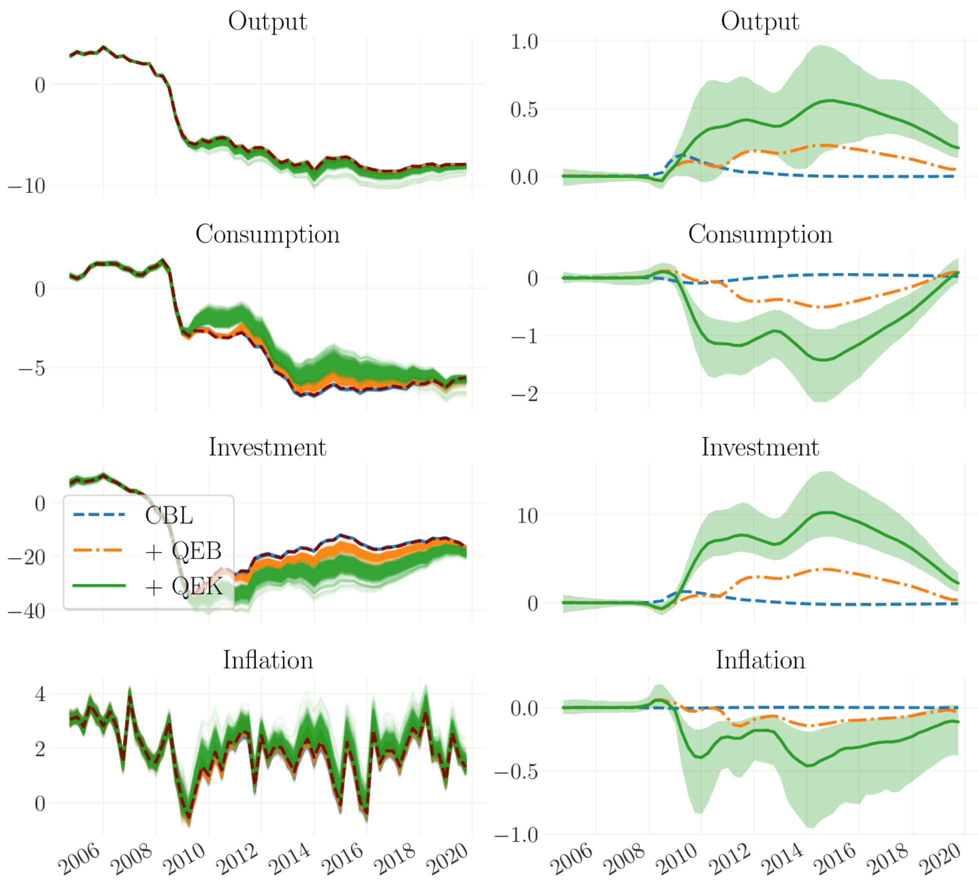

Figure 9: RANK specification of benchmark model. Left: counterfactual simulations without the QE measures. Right: net contribution of each QE measure. Effects in both graphs are cumulative.
Note: Means over 1000 simulations drawn from the posterior. Annual measures where applicable.

fall in consumption with an simultaneous increase in labor supply. The reduced overall effectiveness of QE in stimulating the economy is also mirrored in (i) higher investment adjustment costs which mutes the investment response, (ii) a lower value for the portfolio adjustment costs which implies less limits to arbitrage and (iii) a higher leverage which facilitates a speedy normalization of the financial sector and therefore implies a weaker expansionary impulse for the real economy.

Similarly, Figures 10 and 11 illustrate the counterfactual of how key macroeconomic series would have evolved in the absence of the UMPs through the lens of the H2M vintage of our model. As is the case in our benchmark model, all three UMPs stimulated investment, with the largest effect – an increase of about 7% – coming from the MBS purchases. However, despite this larger response of investment, the overall response of output remains muted relative to our benchmark model. The reason again is a larger fall in aggregate consumption because both, Ricardian and H2M households reduce their

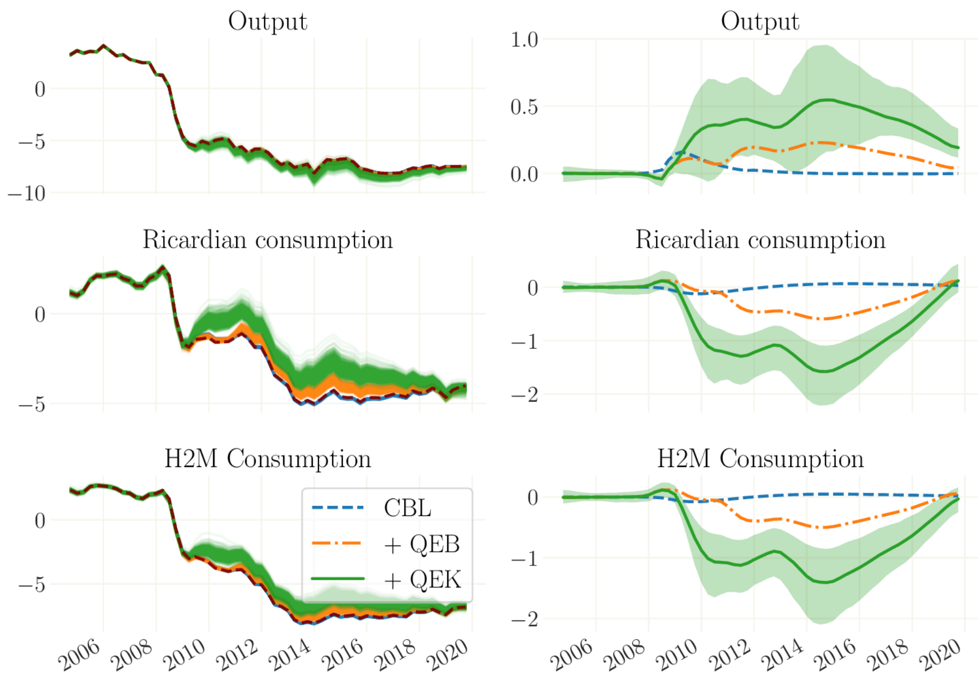

Figure 10: H2M specification of benchmark model. Left: counterfactual simulations without the QE measures. Right: net contribution of each QE measure. Effects in both graphs are cumulative.
Note: Means over 1000 simulations drawn from the posterior. Annual measures where applicable.

consumption. In line with the patient households in our benchmark model, Ricardian households see an increase in the real deposit rate. The latter is even amplified by the larger fall in inflation by -0.5% on average, with the 95% credible set including a fall in the price level of up to 1%. On the other hand, consumption of H2M households actually falls because falling wages reduce their labor income.

Again, these dynamics are reflected in a small set of parameter estimates that differ notably from the benchmark estimation. In order to square the rising labor input induced by QE with an even stronger fall in consumption than in the RANK model, the estimation prefers yet a lower value of $\sigma_l = 0.332$ (instead of 1.231 in the benchmark model and 0.654 in the RANK vintage). Also – as is the case in the RANK model – higher investment adjustment costs, S'' and lower portfolio adjustment costs κ reduce the effectiveness of QE. Finally, we estimate a substantial share of H2M households $\chi = 0.348$, which aligns previous estimates of the literature.[34] Yet note that despite this estimate being larger than our estimated share of impatient households in the benchmark model, both types of households are fundamentally different which makes a direct comparison impossible.

To conclude, both model vintages above show that our results do not hinge on the inclusion of impatient households in the model. In fact, if anything, we find the inclusion

[34] See, e.g., Kaplan et al. (2014).

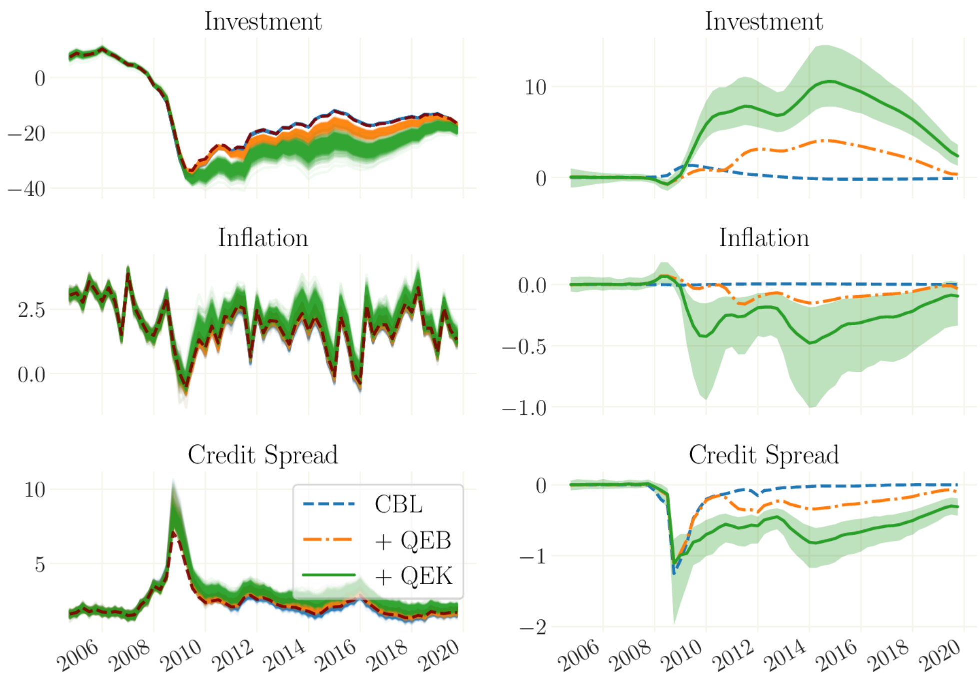

Figure 11: H2M specification of benchmark model. Left: counterfactual simulations without the QE measures. Right: net contribution of each QE measure. Effects in both graphs are cumulative. Measures of spreads and inflation are annualized.
Note: Means over 1000 simulations drawn from the posterior. Annual measures where applicable.

of market segmentation on the household side imply larger effects on economic activity and *less* deflationary effects, together with a *smaller* decline in aggregated consumption. We therefore regard the disinflationary effect presented in the benchmark model as a conservative estimate, which indicates a lower bound.

6.3 Model choice

Besides the framework proposed by Gertler and Karadi (2013) – which serves as a backbone of our financial sector – two other widely used models to study the effects of quantitative easing include Chen et al. (2012) and Carlstrom et al. (2017). Chen et al. (2012) basically add market segmentation and transaction cost to an otherwise standard Smets and Wouters (2007)-type model in line with Andres et al. (2004), such that QE directly affects consumption of restricted households. Our model captures this channel as impatient households have to borrow using long-term private loans, but are effectively restricted from short-term assets. As discussed above, this feature allows QE to affect consumption directly rather than via its effect on the real deposit rate. Carlstrom et al. (2017, henceforth CFP), on the other hand, assume that households are segmented from long-term debt markets and can only save in bank deposits. A hold-up problem – similar in spirit to our bank's moral hazard problem – together with portfolio adjustment costs

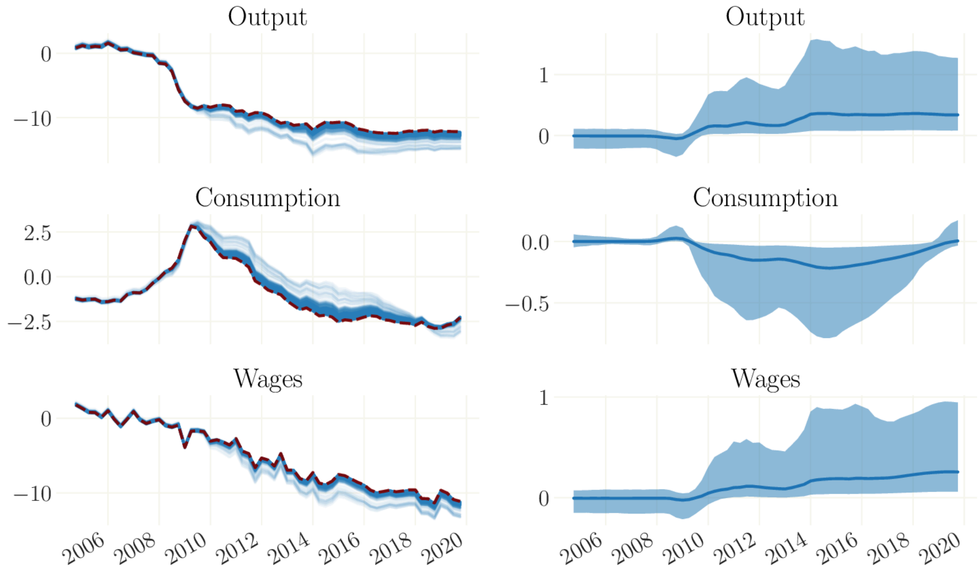

Figure 12: CFP model. Left: counterfactual simulations without the QE measures. Right: net contribution of each QE measure. Effects in both graphs are cumulative.
Note: Means over 1000 simulations drawn from the posterior. Annual measures where applicable.

further limits the financial intermediary from arbitraging yield gaps between short and long-term debt. Lastly, as firms' have to issue long-term debt in oder to finance their capital demand, central bank asset purchases have real effects.

While this model shares several features with ours, there are two important differences. First, the price (and hence yield) of corporate and government bonds is assumed to be same, which restricts us from separating the effects of MBS and government bond purchases. Second, the model does not include a shock that moves consumption and investments into the same direction, which renders the estimation of the GFC difficult, as we will discuss below.[35]

In order to gauge whether our results are also robust to the model choice, we replicate Carlstrom et al. (2017) by estimating their model using their priors, but our nonlinear Bayesian likelihood approach and the same sample period including the ZLB.[36]

We find the sample choice to affect the posterior parameter estimates in a non-negligible way, confirming our intuition of the importance of structural changes in the economy. For instance, we find a substantially steeper wage Phillips curve, despite a notable flatter price Phillips curve. But more broadly, various of our parameter estimates are even outside the 95% credible set reported in CFP. Besides this, the most important difference lies in the estimate of ψ_n, the adjustment costs parameter on net worth, which is the most important driver of QE. We find $\psi_n = 0.14$ instead of 0.7850 reported in

[35]In addition, it is not straightforward to add liquidity injections to the model in a comparable fashion due to the reduced form moral hazard problem.

[36]See the Online Appendix for more details on the data and the parameter estimates.

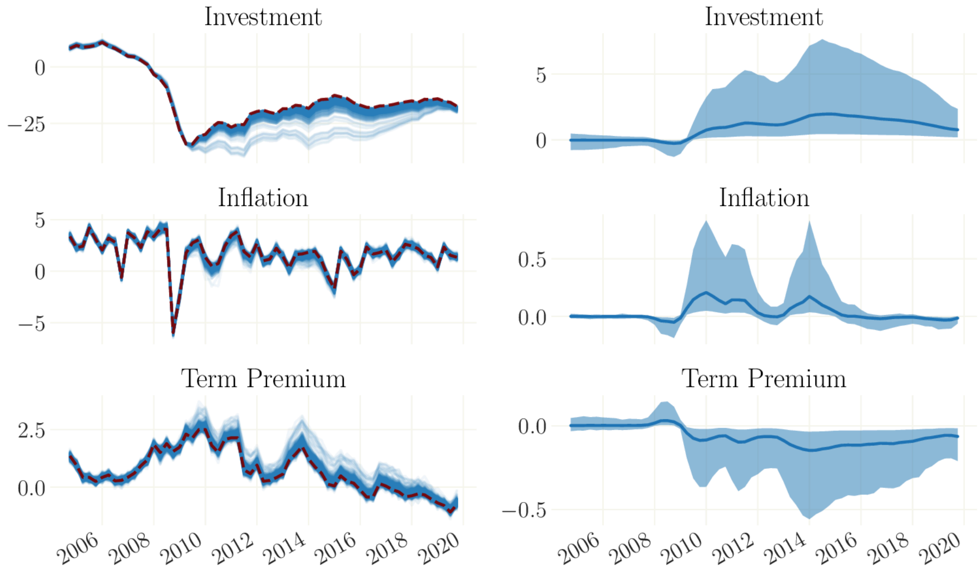

Figure 13: CFP model. Left: counterfactual simulations without the QE measures. Right: net contribution of each QE measure. Effects in both graphs are cumulative.
Note: Means over 1000 simulations drawn from the posterior. Annual measures where applicable.

CFP, which substantially lowers the effectiveness of QE. The reason is that lower net worth adjustment cost imply less limits to arbitrage.

Let us study the counterfactuals of how the key macroeconomic variables would have evolved in the absence of unconventional monetary policy measures in the CFP model. As evident from Figures 12 and 13, MBS and government purchases jointly compress the term premium, albeit only a little, with the peak effect of around -10 basis points. The reason for the latter is our low estimate for the net worth adjustment cost $\psi_n = 0.14$ which govern the limits to arbitrage. The small reduction in the term premium, in turn, translates into similarly muted responses of investment and output. Consumption, on the other hand, falls as it does in our model. Even though the real deposit rate falls, the increase in the return on capital raises the marginal benefits to invest over and above the marginal benefit to consume. So far, the dynamics are consistent with our reported results, although the magnitude is significantly reduced. Contrary to our analysis above, however, inflation seems to fall only initially, but turns positive later on. The latter can be explained by increasing marginal costs. Specifically, without capital utilization, higher investment increases the marginal product of capital. In order to keep the ratio of marginal products constant, also labor demand has to increase mechanically, leading to an increase in wages. Both rising wages and the return on capital which – at first order – equals the marginal product of capital in this model, push up marginal cost and ultimately inflation.

Thus, in contrast to our benchmark model, the demand effects of LSAPs outweigh their supply effects in the estimated CFP model. However, we take this result with a considerable degree of caution. In particular, we argue that the CFP model in its original form is not well suited to study the GFC because it lacks a shock that can explain the joint decline of consumption and investment in the Great Recession. In fact, the historical decomposition suggests that through the lens of the CFP model, the GFC was driven by a negative monetary policy shock. At the same time, CFP do not include consumption as an observable. Following their approach, we see that the smoothed state of consumption suggests that household spending actually peaked in the direct aftermath of the GFC.[37] Both observations let us conclude that the CFP model would require some substantial adjustments to facilitate a meaningful empirical analysis of macroeconomic dynamics in the US on a sample that includes the GFC and its aftermath.

7 Conclusion

After several years of recovery from the Global Financial Crisis, the Federal Reserve embarked again in large-scale asset purchases once the policy rate reached the ZLB in spring 2020. Although the commonly held view points towards expansionary effects of Quantitative Easing, its macroeconomic impact remains unclear. Using a nonlinear Bayesian likelihood approach that fully accounts for the ZLB on nominal interest rates, we are the first to provide a structural investigation of the macroeconomic effects of QE. Our large-scale New Keynesian model includes several channels for QE to have macroeconomic effects and is estimated over the sample from 1998 until 2019 including data of the Federal Reserves balance sheet.

According to our results, the QE programs in the aftermath of GFC had sizable expansionary effects raising output by around 1.2%. This effect was by and large driven by a large increase investment of around 9 percent. Aggregate consumption, on the other hand, contracted by 0.7%. This finding is robust across models and different vintages with a representative agent or heterogeneous agents.

The surge in investment raises the production capacity which caused a disinflationary effect of 0.25 percent. Different to conventional monetary policy, supply side effects of LSAPs seem to dominate the aggregate demand effects, consistent with a cost channel of monetary policy. Our finding of a disinflationary effect of QE is highly policy relevant. In the US, LSAPs create a trade-off for policymakers between the stabilizing prices and employment. For the Euro Area, the result may be even more pressing as its asset purchase programme was explicitly undertaken with the goal to stabilize inflation and inflation expectations at a time when fears of deflation surged.

In times when central banks in developed countries review the robustness of their monetary policy strategies against the backdrop of a higher likelihood of future ZLB episodes, our novel results provide a useful guidance of the macroeconomic effects of large-scale asset purchases. What role wealth or income inequality plays in this context is an important question we leave for future research.

[37] See the Online Appendix. Adding consumption as an observable together with an additional demand shock such as a government spending shock does not resolve this problem since then, consumption is solely explained by this additional shock.

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Appendix A Data

Our eleven observables are mapped into the model equations using the following measurement equations:

$$
\begin{aligned}
\text{Real GDP growth} &= \overline{\gamma} + (y_t - y_{t-1}),\\
\text{Real consumption growth} &= \overline{\gamma} + (c_t - c_{t-1}),\\
\text{Real investment growth} &= \overline{\gamma} + (i_t - i_{t-1}),\\
\text{Real wage growth} &= \overline{\gamma} + (w_t - w_{t-1}),\\
\text{Labor hours} &= \overline{l} + l_t,\\
\text{Inflation} &= \overline{\pi} + \pi_t,\\
\text{Federal funds rate} &= (\frac{\overline{\pi}}{\beta\gamma^{-\sigma_c}} - 1) * 100 + r_t,\\
\text{GZ-spread} &= \overline{spread} + E_t[\widetilde{r}^k_{t+1} - r_t],\\
\text{Gov. bonds purchases} &= \frac{\overline{B}_{cb}}{\overline{Y}} + b_{cb,t},\\
\text{Corp. bonds purchases} &= k_{cb,t},\\
\text{Liquidity injections} &= l^q_t.
\end{aligned}
$$

These observables are constructed as follows:

- GDP: ln(GDP/GDPDEF/CNP16OV_ma)*100
- CONS: ln((PCEC-PCEDG) / GDPDEF / CNP16OV_ma)*100
- INV: ln((GPDI+PCEDG) / GDPDEF / CNP16OV_ma)*100
- LAB: ln(13*AWHNONAG * CE16OV / CNP16OV_ma)*100
- INFL: ln(GDPDEF)*100
- WAGE: ln(COMPNFB / GDPDEF)*100
- FFR: FEDFUNDS/4
- GZ Spread: GZSpread/4
- CB GBonds: TREAST/GDP
- CB CBonds: (WSHOMCB+WCPFF)/GDP
- CB Liquidity: (WACBS + FEDDT + TERAUCT + OTHLT)/GDP

We take log changes for GDP, CONS, INV and WAGE in our measurement equations. Except the GZ spread, which can be downloaded from the Federal Reserves homepage[38], all data is downloaded from the FRED database of the St. Louis Fed, with the above mnemonics representing:

[38] https://www.federalreserve.gov/econresdata/notes/feds-notes/2016/files/ebp_csv.csv

- GDP: GDP - Gross Domestic Product, Billions of Dollars, Quarterly, Seasonally Adjusted Annual Rate, FRED
- GDPDEF: Gross Domestic Product: Implicit Price Deflator , Index 2012=100, Quarterly, Seasonally Adjusted , FRED
- CNP16OV: Civilian noninstitutional population, Thousands of Persons, Quarterly, Seasonally Adjusted, FRED
- CNP16OV_ma: a four-quarter trailing average of CNP16OV
- PCEC: Personal Consumption Expenditures, Billions of Dollars, Quarterly, Seasonally Adjusted Annual Rate, FRED
- PCEDG: Personal Consumption Expenditures: Durable Goods, Billions of Dollars, Quarterly, Seasonally Adjusted Annual Rate, FRED
- GPDI: Gross Private Domestic Investment, Billions of Dollars, Quarterly, Seasonally Adjusted Annual Rate, FRED
- AWHNONAG: Average Weekly Hours of Production and Nonsupervisory Employees: Total private, Hours, Quarterly, Seasonally Adjusted, FRED
- CE16OV: Employment Level, Thousands of Persons, Quarterly, Seasonally Adjusted, FRED
- COMPNFB, Nonfarm Business Sector: Compensation Per Hour, Index 2012=100, Quarterly, Seasonally Adjusted, FRED
- FEDFUNDS: Effective Federal Funds Rate, Percent, FRED
- GZ Spread: A corporate bond credit spread with a high information content for economic activity constructed by Gilchrist and Zakrajšek (2012) using secondary market prices of senior unsecured bonds issued by a large representative sample of US non-financial firms. Quarterly, Percent, Federal Reserve Board.
- TREAST: U.S. Treasury securities held by the Federal Reserve: All Maturities, Millions of Dollars, Quarterly, Not Seasonally Adjusted, FRED
- WSHOMCB: Current face value of mortgage-backed obligations held by Federal Reserve Banks: All Maturities, Millions of Dollars, Quarterly, Not Seasonally Adjusted, FRED
- WCPFF: Net Portfolio Holdings of Commercial Paper Funding Facility LLC, Billions of Dollars, Quarterly, Not Seasonally Adjusted, FRED
- WACBS: Central Bank Liquidity Swaps, Millions of Dollars, Quarterly, Not Seasonally Adjusted, FRED
- FEDDT: Federal agency debt securities held by the Federal Reserve: All Maturities, Millions of Dollars, Quarterly, Not Seasonally Adjusted, FRED

- TERAUCT: Term auction credit held by the Federal Reserve: All Maturities, Millions of Dollars, Quarterly, Not Seasonally Adjusted, FRED
- OTHLT: Other loans held by the Federal Reserve: All Maturities, Millions of Dollars, Quarterly, Not Seasonally Adjusted, FRED

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