CBDC Policies in Open Economies*

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Abstract

We study the consequences for business cycles and welfare of introducing an interest-bearing retail CBDC, competing with bank deposits as medium of exchange, into an estimated 2-country DSGE environment. CBDC issuance of 30% of GDP increases output and welfare by around 6% and 2%, respectively. Financial shocks account for around half of the variance of aggregate demand and inflation, and for the bulk of the variance of financial variables. An aggressive Taylor rule for the interest rate on reserves achieves welfare gains of 0.57% of steady state consumption, an optimized CBDC interest rate rule that responds to a credit gap achieves additional welfare gains of 0.44%, and further gains of 0.57% if accompanied by automatic fiscal stabilizers. A CBDC quantity rule, a response to an inflation gap, a cash-like CBDC, and CBDC as generalized access to reserves, yield significantly smaller gains. CBDC policies can substantially reduce the volatilities of domestic and cross- border banking flows and of the exchange rate. Optimal policy requires a steady state quantity of CBDC of over 40% of annual GDP.

Keywords: Central bank digital currencies, monetary policy, bank deposits, bank loans, monetary frictions, money demand, money supply, credit creation.

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1. Introduction

Central banks worldwide are actively studying the possibility of issuing digital money to the general public, a concept that has become known as central bank digital currencies, or CBDC (Kosse and Mattei (2022)). There have already been significant advances in cross-border wholesale CBDC, where the expected gains were largest.[1] But the full economic potential of CBDC, in all likelihood, has yet to materialize.

While microeconomic and technological benefits of CBDC have so far received most of the attention in the literature, this paper highlights the macroeconomic and financial stability gains that CBDC policies can deliver. In particular, we focus on three questions that are crucial for policymakers, but that have so far received limited attention. First, what are the steady state efficiency gains that can be expected from a *transition* from a pre-CBDC to a post-CBDC economy? Second, how should policymakers design and optimize systematic countercyclical *policy rules* for CBDC? And third, what are the *open-economy* effects of CBDC policies? We will show that CBDC has very sizeable efficiency benefits, that an effective design of CBDC policy rules can further enhance macroeconomic and financial stability, complementing standard monetary and fiscal policy rules, and that both the benefits and side effects of CBDC policies, like those of its monetary and fiscal policy counterparts, are importantly shaped by open-economy considerations. The crucial roles of these aspects and their linkages are important subjects of the ongoing policy discussion (Auer et al. (2021), CPMI et al. (2021)). However, policymakers have so far mostly been having to rely on preliminary macroeconomic assessments that may not be fully backed by solid analytical underpinnings. We aim to fill this gap.

We introduce CBDC into a carefully calibrated and estimated 2-country DSGE environment that features a realistic financial system, and separate policy rules for CBDC and for the interest rate on or the quantity of central bank reserves. Our model builds on Kumhof et al. (2020), where shocks to the supply of credit or to the demand for money, together with the usual real business cycle shocks, give rise to gross as well as net domestic and international capital flows. The specification of the CBDC block of the model builds partly on Barrdear and Kumhof (2021), but it also has a few novel elements.

Our analysis relies on several non-trivial assumptions about the architecture and design features of CBDCs. First, we focus on the retail variety of CBDC that is accessible to households, firms and financial institutions. Second, households and firms are able to hold CBDC (and bank deposits) in both currencies. Third, CBDC is remunerated at an interest rate that, because of CBDC's non-pecuniary convenience yield, remains substantially below the interest rate on central bank reserves – CBDC and reserves are therefore separate forms of central bank money. Fourth, the central bank unconditionally guarantees CBDC issuance against government bonds, while the conversion of bank deposits into CBDC at the central bank may take place at most times, but remains discretionary and contingent. This helps to prevent system-wide or aggregate runs from bank deposits into CBDC (Kumhof and Noone (2021)).

[1] See Auer et al. (2021) for a survey of the state of play among central banks.

For the *transition*, we find that the unilateral introduction of a retail CBDC by a single economy has unambiguously positive effects, yielding long run output gains of just under 6% and long run welfare gains of just over 2% in compensating consumption variation for a CBDC issuance of 30% of GDP. Banks are not crowded out, to the contrary, their balance sheet grows significantly in the long run, while their average cost of funding remains approximately constant.

For *policy rules*, we find that in a contractionary episode the central bank should raise rather than lower the CBDC interest rate relative to the interest rate on reserves and that, if used in this way, a countercyclical CBDC interest rate rule can help to stabilize inflation and output alongside a standard Taylor rule for the interest rate on reserves. However, while for Taylor rules real shocks dominate the welfare results, for CBDC rules financial shocks dominate. We find that CBDC interest rate rules perform better than quantity rules, and that credit gap terms perform better than inflation gap terms in such rules, with the best set of Taylor and CBDC rules yielding welfare gains of around 1% of steady state consumption. Also, in the presence of such rules, automatic fiscal stabilizers become highly effective even if implemented through lump-sum transfers, and deliver further large welfare gains of almost 0.6%. On the other hand, the implementation of CBDC as generalized access to central bank reserves is inferior in welfare terms, and so is a cash-like zero-interest CBDC. Finally, optimal policy calls for saturating the economy with CBDC, specifically for a steady state quantity of CBDC of over 40% of annual GDP, remunerated at a high interest rate.

Turning to the *open economy* dimension, we find that optimized CBDC policies achieve a 30% reduction in exchange rate volatility compared to the data, and a 35% reduction in the volatility of gross cross-border banking exposures relative to pre-CBDC economies with optimized Taylor rules. CBDC does pose the risk of new types of asset demand shocks emerging, namely runs into CBDC. However, under the above-mentioned contingent convertibility rules, and at the level of the aggregate economy, such runs would not be runs from bank deposits but rather runs from government debt securities, and we find that such shocks, even if calibrated to be extremely large, have very small real effects, especially when CBDC is supplied flexibly by the central bank subject to an interest rate rule.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the structural model, which has a pre-CBDC version in which only bank deposits serve as the economy's medium exchange, and a post-CBDC version in which bank deposits and CBDC jointly serve as the medium of exchange. Section 4 discusses the calibration and estimation of a symmetric version of this model, using quarterly data from 1990 to 2019, with the US as the Home economy and the rest of the world as Foreign. Section 5 discusses a simulated transition between the pre-CBDC and post-CBDC models. Section 6 presents quantitative results on optimized simple rules, jointly for a Taylor rule for the interest rate on reserves and a CBDC rule for the interest on or the quantity of CBDC. Section 7 briefly discusses how optimized simple rules compare to two alternatives, the Ramsey optimal policy and a policy that optimizes not only over countercyclical response coefficients but also over a coefficient that determines the steady state quantity of CBDC. Section 8 studies a number of impulse response functions, which help to build intuition for the welfare results and for the transmission mechanism of CBDC policies more generally. Section 9 summarizes and concludes.

2. Literature Review

Our paper contributes to the literature on the nexus between CBDC, banking and macro-financial stability, as well as to the emerging literature on the open economy implications of CBDC.

2.1. CBDC and the Banking Sector

A key aspect of CBDC are its macroeconomic and financial stability implications. These can in turn be divided into two separate issues, longer-run concerns with the disintermediation of banks, and shorter-run concerns with runs on the banking system.

2.1.1. Bank Disintermediation

Many papers in the recent literature outline a mechanism whereby the introduction of CBDC could crowd out deposits and thereby disintermediate banks, including Burlón et al. (2022), Keister and Sanches (2022), Fernández-Villaverde et al. (2021) and Assenmacher et al. (2021). The mechanism for crowding-out proposed by these papers relies on the notion that bank deposits and CBDC are two different types of net investment of a stock of physical saving or net worth that itself exhibits finite elasticity, because preferences for both consumption and work exhibit finite elasticity. As a result, having CBDC absorb a significantly larger share of an inelastic stock of saving requires a smaller stock of bank deposits.[2]

However, bank deposits can be more appropriately characterized as gross financial ledger entries that, as opposed to physical savings, can be created (or destroyed) by the financial system much more elastically than physical resources. The key determinants of these ledger entries are household demands for and bank supplies of gross deposit money and gross loan balances rather than preferences for work and saving. These are only constrained by the profitability calculations of banks and their borrowers, which may depend on the availability of collateral but not on the availability of physically saved resources that can be "lent". When modeling the financial sector as a system of gross ledger entries that takes this into account, as we do in this paper, the bank disintermediation or crowding-out channel becomes quantitatively much less significant or disappears altogether.

2.1.2. Bank Runs

An often-mentioned risk is that bank deposits could be more prone to runs when facing competition from central bank liabilities (Carstens (2019)). To be clear, to the extent that this is seen as a new risk, it must concern the risk of runs from the banking system as a whole to CBDC, rather than runs from an individual institution to other institutions or to central bank money, because these are possible with or without CBDC. The literature suggests that the risk of such aggregate bank runs depends on the design of CBDC.

[2] The main variants of such models where crowding-out does not need to happen are therefore models with infinitely elastic physical saving, such as models with quasi-linear preferences in consumption or hours. Such variants are however typically only employed to make analytical points, and are not meant to be empirically realistic.

Brunnermeier and Niepelt (2019) develop a banking model with money and liquidity frictions, and argue that the introduction of CBDC need not destabilize the banking sector as long as the central bank is willing to acquire potentially unlimited unsecured claims on the banking sector during bank runs, thereby replacing household and firm deposits with central bank deposits and stabilizing bank balance sheets during run episodes. We interpret this result as a useful theoretical benchmark, but as not being intended as a policy prescription. The reason is that such a run would be interpreted as a major crisis that would erode confidence in the financial system, so that practical policy prescriptions instead need to be concerned with how to prevent such events. In our view the key issue here is that this notion of CBDC bank runs presupposes suboptimal CBDC issuance arrangements, and preventing such events only requires avoiding such arrangements.

Our model therefore formalizes the arrangement proposed by Kumhof and Noone (2021), whereby the central bank unconditionally accepts eligible assets, specifically government bonds, in payment for CBDC, while the issuance of CBDC against bank deposits is possible but remains discretionary or conditional. This ensures that bank deposits and central bank money continue to trade at par in all but the most extreme crisis scenarios.[3] It also ensures that bank deposits remain insulated from CBDC-mediated runs, because when the central bank does not issue CBDC against bank checks in a run into CBDC, that run results in a decline in private holdings of government bonds, not of bank deposits. At current levels of government debt, a run into CBDC would have to be extremely large to break that system, and in that extreme case the central bank would still be able to choose between breaking the at par relationship between bank deposits and central bank money on the one hand, and continuing to accept bank deposits in exchange for CBDC and thereby taking potentially extreme risks onto its balance sheet on the other hand.

Fernández-Villaverde et al. (2021) also study the effects of CBDC when bank runs are possible.[4] But while in Brunnermeier and Niepelt (2019) a bank run is the withdrawal of a gross financial balance from one financial institution to another financial institution, in Fernández-Villaverde et al. (2021), as in Diamond and Dybvig (1983), a bank run is the withdrawal of a physical resource for immediate physical consumption. The difficulty with this notion is that a commercial or central bank has no physical resources at its disposal, and their customers do not request physical resources when they withdraw funds in a panic. Instead, they withdraw digital financial balances and deposit them elsewhere, so that the result of a bank run is invariably that the bank in question incurs a liability to clear and settle the outgoing checks of its customers with the recipient institution, which could be either a commercial bank or the central bank.

In our model, there are two shocks that are related to the above notions of runs from bank deposits. The first is a relative preference shock for consumption over deposit holdings, which appears close to the Diamond and Dybvig (1983) notion of a run. However, because such "runs" are non-financial events, they can only happen gradually over time, rather than instantaneously like in a bank run. That is because consumers can never eat enough on a single morning, or even a single quarter, to draw down as many deposits as are lost during a typical bank run. Our model reflects this. The second shock is an increase in the demand for CBDC relative to bank deposits, which has the

[3] Bindseil (2020) instead calls for a tiered interest rate structure on CBDC, with penalty rates for large holdings. Kumhof and Noone (2021) argue that caps high enough to facilitate a sufficient volume of transactions are likely to be too high to contain the risk of bank runs, and that caps would be very hard to set at the right levels especially for large trading firms. On the other hand, insufficient caps would reduce the desirability of CBDC and cause it to not trade at par.

[4] Schilling et al. (2020) develop a nominal model extension of Fernández-Villaverde et al. (2021), with an additional price stability objective for the central bank.

flavor of a Brunnermeier and Niepelt (2019) run. However, only the "into CBDC" portion of such runs can happen in our model, while the assumed issuance arrangements ensure that the "from bank deposits" portion cannot happen in general equilibrium, and is instead replaced with a "from government securities" portion.[5]

2.2. CBDC in Open Economies

Ferrari et al. (2020) focus on the implications of interest-bearing CBDC for exchange rate stability in a two-country model where only one economy issues a global CBDC, and where domestic cash and this global CBDC enter the utility function of both domestic and foreign households separably. They find that the presence of CBDC strengthens international linkages, by serving as an additional asset for cross-border arbitrage that accentuates the response of the exchange rate to shocks.

The main difference to our work is that CBDC in their model is a substitute for cash but not for bank deposits. Our view is that in most economies – certainly in advanced ones – cash is unlikely to be an important factor in the introduction of CBDC,[6] while allowing for the coexistence of bank deposits and CBDC as mediums of exchange permits an analysis of CBDC's effects on financial as well as macroeconomic stability. One result of our analysis is that with optimized policy rules, CBDC does not accentuate, but instead very substantially attenuates, the response of the exchange rate to shocks.[7]

Popescu (2022) studies the effects of CBDC in an open economy model with bank runs. Similar to some of the above-cited closed-economy papers on bank runs, he argues that the presence of a foreign CBDC could increase the risk of financial disintermediation in the domestic banking sector, and result in larger and more volatile capital flows. However, as argued above, the idea of aggregate bank runs into CBDC relies heavily on an assumption of suboptimal CBDC issuance arrangements.

Bacchetta and Perazzi (2021) present a small open economy model that shares some features with ours, including imperfect substitutability between CBDC and bank deposits as mediums of exchange, albeit with the important difference of an exogenously given world real interest rate. They find that the introduction of CBDC facilitates significant steady state welfare gains, and show how this depends on steady state relative interest rates, relative liquidity features, and substitutability between CBDC and bank deposits.

Our paper differs from Bacchetta and Perazzi (2021) in a few dimensions. First, their model is comparatively stylized, with steady state welfare analysis under perfect foresight, while our model is more detailed, with second order approximations used to perform welfare analysis under uncertainty. Second, ours is a two-country model, and is thereby able to track domestic and cross-border balance sheets with matching gross financial positions. Third, we estimate the model, which allows us to

[5] Of course a single household might succeed in running from bank deposits by buying CBDC against bank deposits from another household, but this does not change the overall quantity of bank deposits (or CBDC). An aggregate run is only possible if the central bank is also, unconditionally, a potential counterparty.

[6] Bacchetta and Perazzi (2021) make essentially the same argument.

[7] Cova et al. (2022) present another stylized two-country model with CBDC, where in the benchmark economy the medium of exchange function is also provided by cash only, with no role for bank deposits. They then study the roles of a globally issued stablecoin, and of a zero-interest CBDC that is only accessible in one of the two economies, in perfect foresight simulations of monetary policy shocks. They find that the stablecoin can weaken monetary policy transmission, but that transmission can be restored if the stablecoin is backed by cash, or if CBDC is issued in sufficient quantity.

perform quantitatively realistic analyses of optimized simple policy rules for the interest rate on reserves and for CBDC. We find that the additional welfare gains that are available from such rules, over and above any steady state welfare gains, are very large.

3. The Model

3.1. Overview

We develop a 2-country model of gross domestic and cross-border capital flows, and balance sheet positions, of households and banks. The model is based on Kumhof et al. (2020), and CBDC is introduced as an imperfectly substitutable medium of exchange alongside bank deposits as in Barrdear and Kumhof (2021).

The world economy consists of two countries, Home and Foreign, with respective shares in the world economy of n and $1 - n$. Each country is populated by households (who are also manufacturers), financial investors, unions, banks and a government. In our baseline calibration the two countries are fully symmetric in economic structure, including identical values for all calibrated and estimated parameters. The world economy features Home and Foreign tradable goods and Home and Foreign currencies. There are cross-border financial linkages at household-central-bank, household-commercial-bank, and bank-bank levels. Output is produced by capital and labor, and prices are sticky. Monetary policy follows an inflation forecast based rule for the interest rate on reserves, and another interest rate rule for the interest rate on CBDC (and/or, in some alternatives, a CBDC quantity rule). Fiscal policy follows a deficit rule with or without automatic stabilizers, and deficits are financed through a combination of debt and CBDC. The fiscal block features a full set of carefully calibrated distortionary taxes, as well as lump-sum taxes.

Households consume, subject to habit persistence, and supply labor. They make physical investment decisions and own the domestic capital stock, which serves both as an input into domestic production and as collateral for borrowing from banks. Households and unions have pricing power in goods and labor markets, respectively. Households set prices subject to nominal rigidities, while wages are flexible. Households also make financial investment and borrowing decisions concerning gross retail bank deposits, gross retail bank loans, and retail CBDCs, in both domestic and foreign currencies. Their income consists of wages, capital rentals, net interest income from gross financial positions, profits from the production of goods and of capital, lump-sum profit distributions from unions and banks, and net taxes and transfers. Households, both domestic and foreign, are the only retail borrowers from and retail depositors at banks, and are the sole holders of CBDCs. They consume a CES composite of domestic and foreign traded goods, and they purchase these goods using a CES composite of domestic and foreign currency money. Money in each currency is in turn a CES composite of bank deposits, which are created by banks through loans, and CBDC, which is created by central banks through purchases of government bonds or transfers to the government budget.

Financial investors are not producers or consumers of physical goods. Instead they act as balance sheet managers that represent the domestic wholesale money markets. They hold and arbitrage a portfolio of wholesale bank deposits and government bonds, with the latter benefitting from a small convenience yield due to their important role in financial markets. Financial investors do not hold CBDC on their balance sheets, because as a retail medium of exchange it is not needed by financial investors themselves, while due to its convenience yield it pays a lower interest rate than the wholesale deposits and government bonds preferred by financial investors. Financial investors nevertheless act as market makers in CBDC, because their portfolio of government securities is the eligible asset required by the central bank for additional CBDC issuance. Financial investors transfer part of their interest income to households as lump-sum dividends.

The central bank sets the interest rate on reserves to be consistent with the natural real rate in steady state, while also responding to inflation gaps and output growth over the cycle. The central bank sets the CBDC interest rate or CBDC quantity to target a desired steady state opportunity cost and quantity of CBDC, while also responding to credit or inflation gaps over the cycle. The government issues debt and CBDC, taxes labor, capital and consumption, levies lump-sum taxes, and spends on physical goods and lump-sum transfers. A fiscal rule stabilizes the deficit-to-GDP ratio, and determines how different tax rates are adjusted in response to economic fluctuations.

The banking sector has three functions. The first and second are retail lending and retail deposit issuance, with the terms of loan and deposit contracts chosen to maximize profits. The third is wholesale lending and deposit issuance, with the overall size and composition of the balance sheet chosen to maximize net worth subject to three rules and regulations. First, minimum capital adequacy rules (MCAR) impose either regulatory or business penalties on banks whose capital drops below a specified minimum percentage of total assets. Second, a foreign currency monetary transactions cost (MONFX) requires banks to maintain correspondent accounts with foreign banks in order to compensate for the absence of a lender of last resort in foreign currency. Third, foreign exchange mismatch rules (FXMR) describe either regulatory or business rules on the matching of balance sheet exposures in foreign currency.

We omit cash from the analysis. In modern economies, cash accounts for well under 5% of the broad money supply, and its role is primarily to facilitate small and/or informal transactions while safeguarding privacy, a role that should remain mostly unaffected by the introduction of CBDC.[8]

Home (Foreign) banks issue retail loans to non-banks exclusively in Home (Foreign) currency, and these loans create retail deposits for non-banks in Home (Foreign) currency.[9] Equally, the Home (Foreign) central bank issues CBDC denominated in Home (Foreign) currency. Because of imperfect substitutability in their asset preferences, households must maintain deposit accounts at banks, and CBDC accounts at central banks[10], in both countries. Thus, their cross-border loan and deposit exposures, as well as their cross-border CBDC holdings, are part of the economy's gross and net foreign asset positions, with the remainder accounted for by interbank loan and deposit exposures. A key implication of this setup is that relative currency demands and supplies become an important determinant of exchange rates, alongside relative goods demands and supplies and standard interest parity conditions. This aspect is treated in much greater detail by Cesa-Bianchi et al. (2019).

[8] For public policy purposes, central banks should therefore have an interest in continuing to offer cash.

[9] Cesa-Bianchi et al. (2019) consider the case where banks in each country issue loans in both currencies, but exclusively to households in their respective countries. Their setup gives rise to cross-border financial positions exclusively between banks and not households, and is therefore well-suited to isolate and study the monetary aspects of exchange rate determination, while not being suitable to study many of the capital flow questions addressed in the present paper.

[10] This leaves open the possibility that the private sector could provide the customer-facing front end for CBDC transactions, as long as we assume for modeling purposes that this front end is produced at zero cost.

In the model there are thus four links between the domestic and foreign economies, which are illustrated in Figure 1. First, domestic households purchase foreign goods from foreign households. Second, domestic households hold retail loan and deposit balances at foreign banks. Third, domestic households hold CBDC balances at foreign central banks. Fourth, domestic banks hold interbank loan and deposit balances, so called nostro and vostro accounts, at foreign banks, and in both domestic and foreign currencies.

3.2. Conventions

Except where specifically mentioned, our model description limits itself to the Home economy. Where interactions with Foreign are described, superscript asterisks * indicate Foreign variables. When the discussion applies equally to both countries, we also frequently use the terminology domestic/foreign instead of Home/Foreign.

We observe the convention that a real normalized variable is the nominal variable divided by the price level P_t and the level of global productivity T_t. The exogenous and constant growth rate of global productivity is $x = T_t/T_{t-1}$, while the endogenous and time-varying gross growth rate of the CPI price level is $\pi_t^p = P_t/P_{t-1}$. The nominal exchange rate E_t is the price, expressed in domestic currency, of a unit of foreign currency (so that an increase indicates a depreciation of the domestic currency), and its gross depreciation rate is defined as $\varepsilon_t = E_t/E_{t-1}$. The real exchange rate is defined as the ratio of the two countries' CPI price levels expressed in a common currency, $e_t = \left(E_t P_t^*\right)/P_t$.

Nominal variables are denoted by upper case letters, real variables are denoted by the corresponding lower case letters (for loans, the symbols are L and ℓ), and real normalized variables are denoted by the symbol for the corresponding real variable with a check symbol above the variable. The real value of Home/Foreign currency assets is always expressed in terms of Home/Foreign goods, irrespective of whether the holder is located in Home or Foreign. Home and Foreign goods production and consumption and Home and Foreign currency balance sheet positions are indicated by the subscripts H and F, with shorthand X for $X \in \{H, F\}$. Superscripts h, f and b indicate balance sheet positions of Home households, Foreign households, and banks, with shorthand x for $x \in \{h, f, b\}$.

All interest and inflation rates are in gross terms, and a subscript t on a nominal interest rate denotes an interest rate paid on an asset held from period t to period $t+1$. The real interest rate on a generic domestic currency balance sheet item Z in Home is given by $r_{zH,t} = i_{zH,t-1}/\pi_t^p$, while the real interest rate on a generic foreign currency balance sheet item Z is given by $r_{zF,t} = \left(i_{zF,t-1}\varepsilon_t\right)/\pi_t^p$. We generally describe original optimization problems in nominal and agent-specific form, while optimality conditions are shown in real, normalized (detrended) and aggregate form.

The shocks of the model are, with few exceptions, denoted as S_t^s, where the superscript s denotes the nature of the shock. The shocks have a mean of 1 and are either first-order autocorrelated or i.i.d. The exceptions are government spending $\check{g}_t$, which has a mean different from 1 and follows an ARMA(1,1) process to better match the data, and inventory demand $\check{v}_t$, which has a mean of 0.

3.3. Households

3.3.1. Preferences

Households have unit mass and are indexed by j. They maximize lifetime utility subject to sequences of intertemporal budget constraints and bank participation constraints, by choosing plans for consumption $c_t(j)$, investment $I_t(j)$, hours worked $h_t(j)$, hours hired $H_t(j)$, capital held $k_t(j)$, capital hired $K_t(j)$, retail loans in both currencies $L^h_{X,t}(j)$, retail deposits in both currencies $D^h_{X,t}(j)$, and CBDC holdings in both currencies $M^h_{X,t}(j)$. The objective function of household j is

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta_{hh}^t \left\{ S_t^c \left(1-\frac{\nu}{x}\right) \log\left(c_t(j) - \nu c_{t-1}\right) - \frac{\psi}{2} h_t\left(j\right)^2 \right\} \ , \tag{1}$$

where β_{hh} is the the discount factor, ν parameterizes the degree of external habit persistence, the elasticity of labor supply equals 1, ψ is a labour supply scale parameter, and S_t^c is an autocorrelated consumption demand shock. Households' consumption bundle is a CES aggregate in domestic and foreign goods $c_{H,t}(j)$ and $c_{F,t}(j)$, with consumption home-bias parameter b^c, an autocorrelated import demand shock S_t^m, and elasticity of substitution θ_c:

$$c_t(j) = \left[\left(b^c S_t^m\right)^{1/\theta_c} \left(c_{H,t}(j)\right)^{\frac{\theta_c - 1}{\theta_c}} + \left(1 - b^c S_t^m\right)^{1/\theta_c} \left(c_{F,t}(j)\right)^{\frac{\theta_c - 1}{\theta_c}} \right]^{\frac{\theta_c}{\theta_c - 1}} \ . \tag{2}$$

The corresponding utility-based price index is denoted by P_t. The domestic and foreign goods subaggregates are in turn given by CES bundles over continua of goods, with time-varying elasticities of substitution θ_{p_t}, and therefore with time-varying gross price markups $\theta_{p_t} / \left(\theta_{p_t} - 1\right) = \mu_{p_t} = S_t^{\mu_p} \bar{\mu}_p$, where $S_t^{\mu_p}$ is an i.i.d. price markup shock. We make the conventional assumption that the steady state elasticity of substitution between varieties is greater than the elasticity of substitution between domestic and foreign goods. Demand functions for domestic and foreign goods, as well as for individual goods varieties, are standard.

3.3.2. Technologies

Households are manufacturers of goods. Individual households differ by the goods variety that they produce and sell. Household j optimally hires labour $H_t\left(j\right)$ at the producer wage rate W_t^{pr} and capital $K_t\left(j\right)$ at the user cost R_t^k, to produce and set the prices $P_t(j)$ of one variety j of the domestic good $y_t\left(j\right)$. It does so subject to monopolistic competition and to quadratic price adjustment costs in domestic and foreign markets $G^H_{P,t}(j) = \left(\phi_p/2\right) P_{H,t} y_{H,t} \left(P_{H,t}(j)/P_{H,t-1}(j) - \bar{\pi}\right)^2$ and $G^{H^*}_{P,t}(j) = \left(\phi_p/2\right) E_t P^*_{H,t} y^*_{H,t} \left(P^*_{H,t}(j)/P^*_{H,t-1}(j) - \bar{\pi}\right)^2$, where $P_{H,t}$ is the price of Home goods in Home and $P^*_{H,t}$ is the price of Home goods in Foreign. The production function of household j is given by

$$y_t\left(j\right) = \left(S_t^a T_t H_t\left(j\right)\right)^{1-\alpha} \left(K_t\left(j\right)\right)^{\alpha} \ , \tag{3}$$

where S_t^a is an autocorrelated technology shock.

Households are also producers of the capital stock. To augment the capital stock, which depreciates at the exogenous rate Δ, they exclusively use domestic goods, and are subject to investment adjustment costs and autocorrelated shocks S_t^i to the marginal efficiency of investment,

$$k_t(j) = \left(1-\Delta\right) k_{t-1}(j) + S_t^i I_t(j) \left(1 - \phi_i/2 \left(I_t(j)/\left(x I_{t-1}(j)\right) - 1\right)^2\right) \ . \tag{4}$$

Capital yields a nominal post-tax return $Ret_{k,t} = \left[(1-\Delta) Q_t + R_t^k - \tau_{k,t}\left(R_t^k - \Delta Q_t\right)\right]/Q_{t-1}$ that includes physical rentals, market price appreciation, physical depreciation, and taxes at the rate $\tau_{k,t}$ on rentals net of depreciation. The real return equals $ret_{k,t} = Ret_{k,t}/\left(x\pi_t^p\right)$.

3.3.3. Money Demands

Households face two separate money-in-advance constraints, one for purchases of goods and another for purchases of factors of production.[11] In the first money-in-advance constraint, the nominal monetary aggregate $A_{ci,t}(j)$ is needed to purchase consumption and investment goods,

$$\varkappa^{ci} A_{ci,t}(j) \geq 4 S_t^{mon}\left(P_t c_t(j)\left(1+\tau_{c,t}\right) + P_{H,t} I_t(j)\right) , \tag{5}$$

where $\varkappa^{ci}$ is a velocity constant that determines the size of steady state money demand, the factor 4 annualizes quarterly spending flows, $\tau_{c,t}$ is the consumption tax rate, and S_t^{mon} is an autocorrelated money demand shock. We will think of the latter as a "flight to safety" shock, because an increase in S_t^{mon} represents an increase in the demand for the safety of money balances at the expense of real activity.

The monetary aggregate $A_{ci,t}(j)$ is a nested CES function, with a top level that combines domestic and foreign currency, and a bottom level that combines bank deposits and CBDC in the respective currencies. The top level aggregate features the "financial home bias" parameter b^o, an autocorrelated shock to currency preferences S_t^{ccy}, and the elasticity of substitution θ_o:

$$A_{ci,t}(j) = \left[\left(b^o S_t^{ccy}\right)^{1/\theta_o}\left(O_{H,t}^h(j)\right)^{\frac{\theta_o-1}{\theta_o}} + \left(1-b^o S_t^{ccy}\right)^{1/\theta_o}\left(O_{F,t}^h(j)\right)^{\frac{\theta_o-1}{\theta_o}}\right]^{\frac{\theta_o}{\theta_o-1}} . \tag{6}$$

We will think of shocks to the Foreign $S_t^{ccy^*}$ as "flight to the dollar" shocks (with "Home" representing the US), because a decrease in $S_t^{ccy^*}$ can be thought of as representing an increase in Foreign households' demand for Home currency ("dollars") relative to Foreign currency, at a given level of real activity. The derivatives of the monetary aggregate with respect to its two arguments are denoted by $a_{ci,t}^{H'}(j)$ and $a_{ci,t}^{F'}(j)$. For the two bottom-level monetary aggregates, henceforth abbreviated as *BLMA*, we distinguish between a separable and a nonseparable CES version.

The separable CES version is used for the transition simulation from a pre-CBDC economy to a post-CBDC economy. This allows for zero CBDC balances without thereby taking aggregate money balances to zero in the pre-CBDC economy, and it features decreasing returns to scale and a comparatively high elasticity of substitution (our calibration equals 5). We will discuss in Section 4.1.3 that these are appropriate assumptions for a transition simulation. In nominal terms we have

$$\begin{aligned} O_{H,t}^h(j) &= \left(T_t P_t\right)^{1/\theta_d}\left(\left(D_{H,ci,t}^h(j)\right)^{\frac{\theta_d-1}{\theta_d}} + \left(\eth M_{H,ci,t}^h(j)\right)^{\frac{\theta_d-1}{\theta_d}}\right) , \\ O_{F,t}^h(j) &= \left(T_t P_t\right)^{1/\theta_d}\left(\left(E_t D_{F,ci,t}^h(j)\right)^{\frac{\theta_d-1}{\theta_d}} + \left(\eth^* E_t M_{F,ci,t}^h(j)\right)^{\frac{\theta_d-1}{\theta_d}}\right) , \end{aligned} \tag{7}$$

These are CES aggregates, in that the elasticity of substitution between deposits and CBDC is constant and equals θ_d. But, because $\left(\theta_d-1\right)/\theta_d < 1$, they exhibit decreasing returns to scale. The

[11] We verify that these constraints always bind in equilibrium.

presence of the factor $(T_t P_t)^{1/\theta_d}$ ensures that this functional form nevertheless remains consistent with balanced growth. The constants $\eth$ and $\eth^*$ represent the technological superiority (if $\eth$ and/or $\eth^*$ are greater than 1) of CBDC over deposits in payment transactions.

The nonseparable CES version of the BLMA is used for all simulations where the transition to CBDC has been completed and CBDC is established as a medium of exchange, with the economy now fluctuating around a new steady state. For this type of simulation we prefer a conventional CES specification with constant returns to scale that is consistent with balanced growth. This functional form can also, without (as in (7)) giving rise to excessively decreasing returns to scale, be calibrated with a lower elasticity of substitution of 2. We will discuss the elasticity of substitution in Section 4.1.4. In nominal terms, we have

$$O^h_{H,t}(j) = \left[\left(b^m_{H,ci} S^{ccy}_{H,t} \right)^{1/\theta_d} \left(D^h_{H,ci,t}(j) \right)^{\frac{\theta_d - 1}{\theta_d}} + \left(1 - b^m_{H,ci} S^{ccy}_{H,t} \right)^{1/\theta_d} \left(\eth M^h_{H,ci,t}(j) \right)^{\frac{\theta_d - 1}{\theta_d}} \right]^{\frac{\theta_d}{\theta_d - 1}}, \quad (8)$$

$$O^h_{F,t}(j) = \left[\left(b^m_{F,ci} S^{ccy}_{F,t} \right)^{1/\theta_d} \left(E_t D^h_{F,t}(j) \right)^{\frac{\theta_d - 1}{\theta_d}} + \left(1 - b^m_{F,ci} S^{ccy}_{F,t} \right)^{1/\theta_d} \left(\eth^* E_t M^h_{F,t}(j) \right)^{\frac{\theta_d - 1}{\theta_d}} \right]^{\frac{\theta_d}{\theta_d - 1}},$$

where $S^{ccy}_{H,t}$ and $S^{ccy}_{F,t}$ are portfolio preference shocks to the relative demands for bank deposits relative to CBDC. In the nonseparable case the constant $\eth$ loses the exclusive meaning of technological superiority of CBDC over bank deposits, because in this case the weight of CBDC in money balances (for the first of the above functions) is determined by the joint effects of $\eth$ and the CES preference weight $b^m_{H,ci}$. The derivatives of this aggregate with respect to its arguments are $o^{D'}_{H,t}$ and $o^{M'}_{H,t}$.

In the second money-in-advance constraint, the nominal aggregate $A_{y,t}(j)$ is needed to purchase labor and capital services:

$$\varkappa^y A_{y,t}(j) \geq 4 S^{mon}_t \left(W^{pr}_t H_t(j) + R_{k,t} K_t(j) \right) . \quad (9)$$

As business payments to factors of production are mostly domestic, we assume that there is a single CES monetary aggregate $A_{y,t}(j)$ that combines domestic currency bank deposits $D^h_{H,y,t}$ and CBDC $M^h_{H,y,t}$. Their functional forms are identical to (7) for the transition simulation and (8) otherwise, and their derivatives are denoted by $a^{D'}_{y,t}(j)$ and $a^{M'}_{y,t}(j)$.

We will henceforth refer to the CES money/deposits/CBDC used in the two money-in-advance constraints as consumption money/deposits/CBDC and production money/deposits/CBDC. In our calibration, consumption money will be around four times larger than production money. Where the discussion concerns balance sheet sums rather than CES aggregates of deposits and CBDC, we will use the terminology money balances rather than money. We use the notation $D^h_{H,t} = D^h_{H,ci,t} + D^h_{H,y,t}$ and $M^h_{H,t} = M^h_{H,ci,t} + M^h_{H,y,t}$.

In order to satisfy their demand for deposit money, households need to obtain loans from domestic and foreign banks. In doing so they are subject to small but nonzero real adjustment costs $G^h_{LH,t}(j) = \ell^h_{H,t}(j) \frac{\phi_\ell}{2} \left(\check{\ell}^h_{H,t}(j) - \check{\ell}^h_{H,t-1} \right)^2$ and $G^h_{LF,t}(j) = e_t \ell^h_{F,t}(j) \frac{\phi_\ell}{2} \left(e_t \check{\ell}^h_{F,t}(j) - e_{t-1} \check{\ell}^h_{F,t-1} \right)^2$.

3.3.4. Budget Constraint

The representative household's nominal flow budget constraint, with associated nominal Lagrange multiplier $\Lambda_t^{hh}(j)$, is

$$\begin{aligned}
& \left(D_{H,t}^h(j) + M_{H,t}^h(j)\right)\left(1 + \phi_f\left(b_t^{rat} - \bar{b}_{ss}^{rat}\right)\right) + E_t\left(D_{F,t}^h(j) + M_{F,t}^h(j)\right)\left(1 + \phi_f^*\left(b_t^{rat^*} - \bar{b}_{ss}^{rat^*}\right)\right) \\
& + Q_t k_t(j) - P_t \Psi_t(j) - L_{H,t}^h\left(1 - G_{LH,t}^h(j)\right) - E_t L_{F,t}^h(j)\left(1 - G_{LF,t}^h(j)\right) \qquad (10) \\
= \; & i_{dH,t-1}^h D_{H,t-1}^h(j) + i_{mH,t-1}^h M_{H,t-1}^h(j) + E_t i_{dF,t-1}^h D_{F,t-1}^h(j) + E_t i_{mF,t-1}^h M_{F,t-1}^h(j) \\
& + Ret_{k,t} Q_{t-1} k_{t-1}(j)\left(1 - \kappa_H^h S_{t-1}^{cred} \Gamma_{H,t}^h(j) - \kappa_F^{h^*} \Gamma_{F,t}^{h^*}(j)\right) + \varpi^k \tau_{k,t}\left(R_t^k - \Delta Q_t\right) k_{t-1} \\
& + W_t^{wo} h_t(j)\left(1 - \tau_{L,t}\right) + \varpi^h \tau_{L,t} W_t^{wo} h_t + P_t \Upsilon_t(j) \\
& + P_{H,t}(j)\, y_{H,t}(j) + E_t P_{H,t}^*(j)\, y_{H,t}^*(j) - W_t^{pr} H_t(j) - R_{k,t} K_t(j) - G_{P,t}(j) \\
& + Q_t\left(k_t(j) - (1 - \Delta) k_{t-1}(j)\right) - P_{H,t} I_t(j) - P_t c_t(j)\left(1 + \tau_{c,t}\right) - P_{H,t} v_t(j)\,.
\end{aligned}$$

Portfolio costs: The term $\phi_f\left(b_t^{rat} - \bar{b}_{ss}^{rat}\right)$, where $b_t^{rat} = B_t / \left(4GDP_t\right)$ is the government debt-to-GDP ratio and $\bar{b}_{ss}^{rat}$ is its initial steady state, represents transactions costs related to the holding of domestic financial assets, with a similar term for foreign financial assets. This cost is taken as exogenous by households, and $P_t \Psi_t(j)$ represents the its lump-sum distribution back to households. This allows the model to replicate the small but positive elasticity of equilibrium real interest rates with respect to the level of government debt that is found in the empirical literature. Interest rates on all financial assets in a given currency are affected in the same fashion, so that a change in the government debt-to-GDP ratio, ceteris paribus, will affect the level of interest rates but not the structure of spreads.

Taxation: In order to accurately account for both incentive effects and budgetary effects of income taxes, the model distinguishes between marginal and average tax rates on labor and capital (for consumption taxes $\tau_{c,t}$, the marginal and average tax rates are equal). The tax base for the labor income tax is $W_t^{wo} h_t(j)$, where W_t^{wo} is the nominal wage paid by unions to workers, while the tax base for the capital income tax is $\left(R_t^k - \Delta Q_t\right) k_{t-1}(j)$. The marginal tax rates are $\tau_{L,t}$ and $\tau_{k,t}$. The average tax rates are $\tau_{L,t}\left(1 - \varpi^h\right)$ and $\tau_{k,t}\left(1 - \varpi^k\right)$, where ϖ^h and ϖ^k are tax exemptions for inframarginal income. Tax exemptions appear in the household and government budget constraints, but they do so without the index j, as $\varpi^h \tau_{L,t} W_t^{wo} h_t$ and $\varpi^k \tau_{k,t}\left(R_t^k - \Delta Q_t\right) k_{t-1}$. This means that exemptions affect budgets, but they do not affect marginal conditions. Also, this formulation ensures that in equilibrium the ratio of marginal to average tax rates remains constant at all times.

Assets and liabilities: The left-hand side shows households' gross asset and liability positions, namely deposits and CBDC in each currency, plus capital, minus loans in each currency. The first and second line on the right-hand side show the gross nominal returns on assets held in the previous period. Households' return to capital includes a tax rebate on inframarginal income $\varpi^k \tau_{k,t}\left(R_t^k - \Delta Q_t\right) k_{t-1}$. It excludes returns that go to banks to repay loans, where $\Gamma_{H,t}^h(j)$ and $\Gamma_{F,t}^{h^*}(j)$ are the endogenous shares of the gross returns of collateral capital that go to the lenders to repay loans, $\kappa_H^h S_{t-1}^{cred}$ and $\kappa_F^{h^*}$ are the shares of domestic capital accepted as collateral by domestic and foreign banks, and S_t^{cred} is an autocorrelated shock to credit supply. An increase in S_t^{cred} leads to a credit boom that both increases the quantity and reduces the cost of credit and thus of deposit money creation.

Other income and expenditures: Other than net asset income, households receive labor income and lump-sum net income. Wages are paid net of labor income taxes. The return to labor includes a tax rebate on inframarginal income $\varpi^h \tau_{L,t} W_t^{wo} h_t$. Lump-sum net income $P_t \Upsilon_t(j)$ equals the sum of profits and dividends of unions $P_t \Pi_t^U(j)$, financial investors $P_t \Pi_t^{FI}(j)$, and banks $\delta_b N_t^b(j)$, the net balance of fiscal transfers $P_t trf_t(j)$ and lump-sum taxes $P_t \tau_t^{ls}(j)$, and a share $1 - \mathfrak{r}$ of price, wage and loan adjustment costs, and of banks' monetary transactions, loan monitoring, and regulatory penalty costs. The remaining share $\mathfrak{r}$ is treated as a real resource cost. The net income of households in their role of goods producers is given by nominal sales revenue $P_{H,t}(j) \, y_{H,t}(j) + E_t P_{H,t}^*(j) \, y_{H,t}^*(j)$ minus payments of wages W_t^{pr} to labor hired $H_t(j)$, of capital rentals R_t^k to capital hired $K_t(j)$, and price adjustment costs $G_{P,t}(j)$. The net income of households in their role as capital producers is given by the difference between the market value of additional capital produced $Q_t \left(k_t(j) - (1-\Delta) \, k_{t-1}(j)\right)$, where Q_t is Tobin's q, and the purchase cost of investment goods $P_{H,t} I_t(j)$. Other household expenditures include consumption purchases $P_t c_t(j) \, (1 + \tau_{c,t})$ and inventory purchases $P_{H,t} v_t(j)$. The latter are exogenous and stochastic with mean zero and a small standard error. They are needed to better match the data for real GDP, as has also been found in quantitative models used by central banks (e.g. Burgess et al. (2013)).[12]

3.3.5. Gross Capital Flows

The left-hand side of (10) shows why the assumption of a representative household that both borrows from and holds deposits with banks is crucial for the modeling of gross capital flows, gross balance sheet positions, and the drivers of deposit growth (Jakab and Kumhof (2018)). Domestic gross positions, with domestic banks, are given by $D_{H,t}^h(j)$ and $L_{H,t}^h(j)$, with a net position of $D_{H,t}^h(j) - L_{H,t}^h(j)$, while foreign gross positions, with foreign banks, are given by $E_t D_{F,t}^h(j)$ and $E_t L_{F,t}^h(j)$, with a net position of $E_t \left(D_{F,t}^h(j) - L_{F,t}^h(j) \right)$.

This shows that, first, *deposit growth only requires loan growth*, with no role at all for saving.[13] The fact that, after a new loan has been disbursed, the new deposit changes hands between different households does not change the fact that aggregate deposits must remain unchanged until this or some other loan is repaid. Second, in the absence of loan growth, *deposit growth cannot be driven by saving*. When household j_1 saves[14] by making a deposit of a check paid to him by another household j_2, this check only has value because it is drawn on j_2's existing bank deposit in another bank. This changes the location of existing bank deposits within the banking system, but it cannot lead to an overall increase in bank deposits. Saving is therefore not only unnecessary for deposit growth, it cannot by itself contribute to deposit growth at all. It can only do so if it happens to be accompanied by lending, such as when an investor pays the producer of a machine with a check that represents the disbursement of a new loan.

[12] Iacoviello et al. (2011) use a more elaborate specification with input and output inventories that are accumulated and used in production. Our own formulation is more closely related to the standard treatment of government spending in DSGE models, in that inventories are wasted. The only difference is that inventories, unlike government spending, have a mean of zero.

[13] In the interest of simplicity, we abstract here from a few other real-world drivers of deposit growth. The most important of these are bank net purchases of securities and bank payments to workers and suppliers. These are however quantitatively far less significant than loan growth.

[14] Note that saving here encompasses both national accounts saving, such as when household j_1 has received a check in payment of a new investment good, and interpersonal saving, such as when j_1 has received a check in payment of existing physical assets, financial assets, or perishable goods.

Gross positions are also highly relevant for an understanding of financial flows, and this includes international capital flows (Kumhof et al. (2020)). Credit creation for a domestic resident by a foreign bank represents one of the most elementary forms of gross international financial (i.e. not involving goods trade) flows, which always have two inseparable legs, a gross inflow (the deposit) and a gross outflow (the loan), with no implications, ceteris paribus, for saving, the current account, and the net foreign asset position. The presence of CBDC does not change this logic.

3.3.6. Participation Constraints

Households also face participation constraints for taking out loans in domestic and foreign currency, whose derivation will be explained below. For Home households we have

$$\begin{aligned} \mathbb{E}_t \left[\kappa_H^h S_t^{cred} Ret_{k,t+1} Q_t k_t(j) \left(\Gamma_{H,t+1}^h(j) - \xi_H^h G_{H,t+1}^h(j) \right) - i_{\ell H,t}^h L_{H,t}^h(j) \right] &= 0 \; , \qquad (11) \\ \mathbb{E}_t \left[\kappa_F^{h^*} Ret_{k,t+1} Q_t k_t(j) \left(\Gamma_{F,t+1}^{h^*}(j) - \xi_F^{h^*} G_{F,t+1}^{h^*}(j) \right) - E_{t+1} i_{\ell F,t}^h L_{F,t}^h(j) \right] &= 0 \; , \end{aligned}$$

with multipliers $\Lambda_t^{hh}(j)\tilde{\Lambda}_{H,t+1}^h(j)$ and $\Lambda_t^{hh}(j)\tilde{\Lambda}_{F,t+1}^h(j)$, and where $L_{F,t}^h(j)$ is in Foreign currency but Home per capita terms. The terms $\xi_X^x G_{X,t+1}^x(j)$ denote lenders' endogenous monitoring cost share in pledged gross returns to capital.

3.3.7. Optimality Conditions

We assume that each household holds identical initial stocks of all physical and financial assets and liabilities and receives identical net lump-sum transfers. Because all households face the same market prices, and ex-post set the same prices for their own product varieties, they remain symmetric at all times. The index j can therefore be dropped when stating the optimality conditions, which are presented in real normalized form.

In the optimality conditions for aggregate consumption, investment, labor input, and capital input, the effective price exceeds the direct purchase price by a mark-up due to monetary frictions. There is an equivalence between distortionary fiscal tax rates and these mark-ups, which will therefore be referred to as money tax rates τ^{mon}:

$$\tau_{x,t}^{mon} = \lambda_t^x S_t^{mon} 4 \; , \; x \in \{ci, y\} \; . \qquad (12)$$

The multipliers of the money-in-advance constraints λ_t^x are decreasing in money provision by either banks or, in the case of CBDC, the central bank. In the optimality conditions for deposits and CBDC, the asset return includes both a gross financial or interest rate yield and a net nonfinancial or convenience yield r^{cy}. For the example of Home currency consumption CBDC this convenience yield is

$$r_{ci,H,M,t}^{cy} = \lambda_t^{ci} \varkappa^{ci} a_{ci,t}^{H'} o_{H,t}^{M'} \; . \qquad (13)$$

The first-order condition for hours worked and the two price Phillips curves are standard, and are omitted to conserve space. The first-order condition for capital has several additional terms related to the use of capital as loan collateral, but is also omitted. The first-order condition for consumption is

$$\frac{S_t^c \left(1 - \frac{\nu}{x}\right)}{\check{c}_t - \frac{\nu}{x}\check{c}_{t-1}} = \check{\lambda}_t^{hh} \left(1 + \tau_{c,t}\right) \left(1 + \tau_{ci,t}^{mon}\right) \; . \qquad (14)$$

The term $1+\tau^{mon}_{ci,t}$ is the effective price of consumption. The first order conditions for investment and inputs have similar terms:

$$q_t S^i_t = p_{H,t}\left(1+\tau^{mon}_{ci,t}\right) + \phi_i q_t S^i_t \left(\frac{\check{I}_t}{\check{I}_{t-1}}\right)\left(\frac{\check{I}_t}{\check{I}_{t-1}}-1\right) - \beta_{hh}\mathbb{E}_t \frac{\check{\lambda}^{hh}_{t+1}}{\check{\lambda}^{hh}_t}\phi_i q_{t+1} S^i_{t+1}\left(\frac{\check{I}_{t+1}}{\check{I}_t}\right)^2\left(\frac{\check{I}_{t+1}}{\check{I}_t}-1\right) , \tag{15}$$

$$\check{w}^{pr}_t h_t \left(1+\tau^{mon}_{y,t}\right) = (1-\alpha)\, mc_t \check{y}_t , \tag{16}$$

$$r_{k,t}\frac{\check{k}_{t-1}}{x}\left(1+\tau^{mon}_{y,t}\right) = \alpha mc_t \check{y}_t . \tag{17}$$

The first-order Euler condition for domestic currency consumption CBDC, using (13) above, is

$$1+\phi_f\left(b^{rat}_t - \bar{b}^{rat}_{ss}\right) - r^{cy}_{ci,H,M,t} = \mathbb{E}_t \frac{\beta_{hh}}{x}\frac{\check{\lambda}^{hh}_{t+1}}{\check{\lambda}^{hh}_t} r_{m,t+1} . \tag{18}$$

We omit the conditions for domestic currency production CBDC, for foreign currency consumption CBDC, and for the three deposit balances, as they take the same form. The condition states that, as long as $b^{rat}_t = \bar{b}^{rat}_{ss}$, the product of the intertemporal marginal rate of substitution and the CBDC interest rate is less than one due to the marginal convenience yield of CBDC, whose size is inversely related to the quantity of CBDC. This can be used to compute the steady state interest semi-elasticity of CBDC demand ϵ^{hh}_m, which measures the increase, in percent, of households' demand for CBDC in response to a one percentage point increase in the annualized spread between the domestic currency CBDC rate $i_{m,t}$ and the domestic currency deposit rate $i^h_{dH,t}$. Combining the two first-order conditions for domestic and foreign currency deposits, or CBDC, yields expressions that Cesa-Bianchi et al. (2019) refer to as monetary UIP (MUIP) spreads, which capture the effects on interest parity and exchange rates of changes to the relative convenience yield of the two currencies. The first-order condition for domestic currency loans is

$$1-\frac{\phi_\ell}{2}\left(\check{\ell}^h_{H,t}-\check{\ell}^h_{H,t-1}\right)^2 - \phi_\ell \check{\ell}^h_{H,t}\left(\check{\ell}^h_{H,t}-\check{\ell}^h_{H,t-1}\right) = \frac{\beta_{hh}}{x}\mathbb{E}_t \frac{\check{\lambda}^{hh}_{t+1}}{\check{\lambda}^{hh}_t}\left(\Gamma^{h,\omega}_{H,t+1} / \left(\Gamma^{h,\omega}_{H,t+1} - \xi^h_H G^{h,\omega}_{H,t+1}\right)\right) r^h_{\ell H,t+1} , \tag{19}$$

where $r^h_{\ell H,t}$ is the real wholesale lending rate, while $\Gamma^{h,\omega}_{H,t}$ and $G^{h,\omega}_{H,t}$ are the derivatives of $\Gamma^h_{H,t}$ and $G^h_{H,t}$ with respect to the cutoff productivity $\bar{\omega}^h_{H,t}$. We omit the condition for foreign currency loans, as it takes the same form.

3.4. Unions

Unions have unit mass and are indexed by j, where individual unions differ by the labour variety they sell. Unions buy homogenous labor from households at a nominal worker wage rate W^{wo}_t set in a competitive labor market. They set the price of their labor variety $W^{pr}_t(j)$ subject to monopolistic competition. Employers demand a composite of labor varieties with elasticity of substitution θ_{w_t}, and therefore with time-varying gross wage markups $\theta_{w_t}/(\theta_{w_t}-1) = \mu_{w_t} = S^{\mu_w}_t \bar{\mu}_w$, where $S^{\mu_w}_t$ is an i.i.d. wage markup shock. Unions are owned by households, to whom their profits $\check{\Pi}^U_t$ are transferred in a lump-sum fashion.

3.5. Financial Investors

Financial investors have unit mass and are indexed by j. They are not producers or consumers of physical goods, and can therefore be ignored in welfare calculations. Instead they act as balance sheet managers that represent the domestic wholesale money markets, where they trade government securities and wholesale bank deposits under the assumption of very high interest sensitivity. Financial investors are the sole investors in domestic government securities $B_t(j)$ that pay the nominal interest rate $i_{b,t}$, and that have a small but positive convenience yield due to their important role in financial markets (Krishnamurthy and Vissing-Jorgensen (2012)). Their net holdings of wholesale deposits are denoted by $D_t^{fi}(j)$ and pay the wholesale interest rate $i_{w,t}$. Financial investors also make a market in wholesale deposits by being both a taker (from retail deposit banks) and maker (at wholesale banks) of these deposits, with zero transactions costs and therefore at the same wholesale interest rate $i_{w,t}$. Financial investors do not hold CBDC (except intra-day for their customers), because as a retail medium of exchange it is not needed by financial investors themselves, while due to its convenience yield it pays a lower interest rate than the wholesale deposits and government bonds preferred by financial investors. Financial investors nevertheless act as a market maker in CBDC, because their government securities are the only asset against which the central bank will issue additional CBDC. Financial investors transfer part of their net interest earnings to households as dividends $\Pi_t^{fi}(j)$, subject to dividend smoothing modelled as external habit persistence. The objective function for financial investor j is

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta_{fi}^t \left\{ S_t^c \left(1 - \frac{\nu}{x}\right) \log\left(\Pi_t^{fi}(j) - \nu \Pi_{t-1}^{fi}\right) + \gamma \frac{\left(\frac{b_t(j)}{T_t}\right)^{1-\vartheta_{fi}}}{1-\vartheta_{fi}} \right\} \tag{20}$$

where v has the same value as for households, while β_{fi} differs from β_{hh}. Because our objective is to represent the highly interest-sensitive nature of wholesale money markets, a bonds-in-the-utility-function term replaces the money-in-advance friction of households. The nominal budget constraint is given by

$$\left(B_t(j) + D_t^{fi}(j)\right)\left(1 + \phi_f\left(b_t^{rat} - \bar{b}_{ss}^{rat}\right)\right) = i_{b,t-1}B_{t-1}(j) + i_{w,t-1}D_{t-1}^{fi}(j) + P_t\Psi_t^{fi}(j) - P_t\Pi_t^{fi} \tag{21}$$

The optimality condition for dividends is $S_t^c\left(1 - \frac{\nu}{x}\right) / \left(\check{\Pi}_t^{fi} - \frac{\nu}{x}\check{\Pi}_{t-1}^{fi}\right) = \check{\lambda}_t^{fi}$. The first-order condition for government securities is

$$\check{\lambda}_t^{fi}\left(1 + \phi_f\left(b_t^{rat} - \bar{b}_{ss}^{rat}\right)\right) - \gamma\left(\check{b}_t\right)^{-\vartheta_{fi}} = \mathbb{E}_t \frac{\beta_{fi}}{x}\left(\check{\lambda}_{t+1}^{fi} r_{b,t+1}\right) \ , \tag{22}$$

where $r_{b,t}$ is the real interest rate on government securities, while the first-order condition for wholesale deposits is

$$\check{\lambda}_t^{fi}\left(1 + \phi_f\left(b_t^{rat} - \bar{b}_{ss}^{rat}\right)\right) = \frac{\beta_{fi}}{x} E_t\left(\check{\lambda}_{t+1}^{fi} r_{w,t+1}\right) \ . \tag{23}$$

The last two conditions imply a spread between the two interest rates that is due to the monetary convenience yield of government securities. The steady state level of this spread is assumed to be small but positive, while the interest semi-elasticity of the demand for these securities ϵ_b^{fi} is very high. This semi-elasticity measures the decrease, in percent, of financial investors' demand for government securities in response to a one percentage point increase in the annualized spread between the wholesale money market rate $i_{w,t}$ and the rate on government securities $i_{b,t}$.

3.6. Banking Sector

The three functions of the banking sector are wholesale lending and deposit issuance, retail deposit issuance, and retail lending. For analytical convenience, we split banks' optimization problem into these three components, and assign them to different sectors within the banking system. Banks are price takers in retail lending and wholesale markets and price setters in retail deposit markets. As result, loan and deposit pricing are separable decisions, with loan pricing based exclusively on wholesale funding costs.

3.6.1. Wholesale Banks

Wholesale banks have unit mass and are indexed by j. They maximize net worth subject to rules and regulatory constraints, and are ex-ante identical in terms of ratios of assets and liabilities to net worth, while they may differ in terms of the size of net worth. They issue wholesale loans in domestic currency to two domestic retail lending banking sectors that in turn lend to domestic and foreign households. Aggregate wholesale loans to households are denoted by $L_t^\ell(j) = L_{H,t}^h(j) + L_{H,t}^f(j)$. Wholesale banks also issue interbank loans (nostro accounts) in domestic currency $L_{H,t}^b(j)$ to foreign wholesale banks, hold interbank deposits (nostro accounts) in foreign currency $D_{F,t}^b(j)$ at foreign retail deposit banks, receive interbank loans (vostro accounts) in foreign currency $L_{F,t}^b(j)$ from foreign wholesale banks, and maintain interbank deposits (vostro accounts) in domestic currency $D_{H,t}^b(j)$ for foreign wholesale banks. Gross assets are subject to lognormally distributed idiosyncratic shocks ω_{t+1}^b with mean 1 and variance $(\sigma^b)^2$ that represent shocks to banks' non-interest earnings, and that give rise to ex-post differences across banks in terms of capital adequacy. We denote the pdf and cdf of these shocks by $f^b(\omega_{t+1}^b)$ and $F^b(\omega_{t+1}^b)$, the cutoff productivity shocks below which bankruptcy occurs ex-post by $\bar{\omega}_t^b$, and we define $f_t^b = f^b(\bar{\omega}_t^b)$ and $F_t^b = F^b(\bar{\omega}_t^b)$. Other than interbank balances, the principal liability of wholesale banks consists of wholesale deposits in domestic currency $D_t^d(j) = D_t^{fi}(j) + D_{H,t}^h(j) + D_{H,t}^f(j)$. Their net worth, which is held by domestic households, is $N_t^b(j)$. An individual wholesale bank's balance sheet is therefore given by

$$L_t^\ell(j) + L_{H,t}^b(j) + E_t D_{F,t}^b(j) = D_t^d(j) + D_{H,t}^b(j) + E_t L_{F,t}^b(j) + N_t^b(j) \ . \tag{24}$$

Minimum capital adequacy rules (MCAR) limit wholesale banks' ability to create credit and therefore money. Bank j faces a future penalty of $\chi \frac{P_{t+1}}{P_t} \left[L_t^\ell(j) + L_{H,t}^b(j) + E_t D_{F,t}^b(j) \right]$ if in the next period net worth falls short of ΘS_t^{lev} times risk-weighted assets. Net worth equals the difference between the gross returns on asset-side and liability-side items, plus the net profits of retail deposit and retail lending banks, minus monetary transaction costs (see below). Risk-weighted assets equal the risk-weight-adjusted gross returns on all asset-side items, where the regulatory risk weight on loans to households equals 1 while the regulatory risk-weight on interbank positions equals $\zeta < 1$. The expression for the equilibrium share $\bar{\omega}_t^b$ of banks that does not meet MCAR ex-post is not shown to conserve space. We interpret the steady state level of Θ as being determined by capital adequacy regulation, while shocks to S_t^{lev} capture banks' temporary changes in preferences for leverage. Total ex-post regulatory penalties for bank j equal $\mathcal{M}_t^b(j)$.

Monetary foreign exchange related transaction costs (MONFX) reflect the fact that banks' exposures to foreign households are costlier to maintain than exposures to domestic households. The reason is that the absence of a lender of last resort in foreign currency requires that banks self-insure, by maintaining readily accessible foreign currency funds in nostro correspondent accounts at foreign banks, to facilitate conversions between foreign and domestic currencies when loans to foreigners are made or repaid. This is modelled as a monetary transactions cost that is increasing in loans to foreign households $L^f_{H,t}(j)$ and decreasing in interbank foreign currency deposit balances $E_t D^b_{F,t}(j)$. We choose the functional form $s^b_t(j) L^f_{H,t}(j)$, where $s^b_t(j) = (\varphi_b/\vartheta_b)\left(e_t \check{d}^b_{F,t}(j)\right)^{-\vartheta_b}$. Total ex-post MONFX transaction costs for bank j equal $\mathfrak{I}^b_t(j)$.

Foreign exchange mismatch rules (FXMR) describe banks' management of foreign currency exposures. As pointed out in Aldasoro et al. (2020)[15], due to both risk management practices and prudential regulations, banks avoid significant open foreign exchange positions, in practice by using foreign exchange swaps and other derivatives. In our model we therefore adopt the strict FXMR rule that all foreign currency positions must be matched at all times, for both countries. For Home, we have

$$D^b_{F,t}(j) - L^b_{F,t}(j) = 0 \; . \tag{25}$$

Net worth maximization involves taking first-order conditions with respect to all four asset side items, taking interest rates as given. Gross nominal wholesale lending rates are denoted by $i^x_{\ell H,t}$, and can be interpreted as the rates banks would charge to riskless borrowers (these are not present in the model). The gross wholesale deposit interest rate facing banks is denoted by $i_{w,t}$, and the lump-sum terms $\Pi^R_t(j)$ and $\Lambda^b_t(j)$ denote the net ex-post profits of retail deposit banks and the net ex-post losses of retail lending banks. Banks internalize the risk of breaching the MCAR, so that expected net worth includes the penalty payable if a breach occurs, weighted by the probability of a breach. We have the following optimization problem:

$$\begin{aligned} \max \mathbb{E}_t \Big\{ & \left[i^h_{\ell H,t} L^h_{H,t}(j) + i^f_{\ell H,t} L^f_{H,t}(j) + i^b_{\ell H,t} L^b_{H,t}(j) + E_{t+1} i^b_{dF,t} D^b_{F,t}(j) \right] \omega^b_{t+1} \\ & - i_{w,t} D^d_t(j) - E_{t+1} i^b_{\ell F,t} L^b_{F,t}(j) \\ & - s^b_t(j) L^f_{H,t}(j) + P_{t+1}\left(\Pi^R_{t+1}(j) - \Lambda^b_{t+1}(j) \right) \\ - \int_0^{\bar{\omega}^b_{t+1}(j)} & \chi \frac{P_{t+1}}{P_t} \left(L^h_{H,t}(j) + L^f_{H,t}(j) + L^b_{H,t}(j) + E_t D^b_{F,t}(j) \right) f^b\left(\omega^b_{t+1}\right) d\omega^b_{t+1} \Big\} \end{aligned} \tag{26}$$

The deposit terms in this expression and in the expression for $\bar{\omega}^b_{t+1}(j)$ must be replaced using a combination of the balance sheet identity (24) and the FXMR rule (25). Post-dividend net worth equals the above expression minus dividends that equal a fixed fraction of net worth, and that are paid out to households in a lump-sum fashion, a specification that can be obtained by applying the "extended family" approach of Gertler and Karadi (2011). The law of motion for ex-post nominal wholesale bank net worth is therefore

$$\begin{aligned} N^b_t(j) = {} & i^h_{\ell H,t-1} L^h_{H,t-1}(j) + i^f_{\ell H,t-1} L^f_{H,t-1}(j) + i^b_{\ell H,t-1} L^b_{H,t-1}(j) + i^b_{dF,t-1} E_t D^b_{F,t-1}(j) - i_{w,t-1} D^d_{t-1}(j) \\ & - i^b_{\ell F,t-1} E_t L^b_{F,t-1}(j) - P_t \left(\mathcal{M}^b_t(j) + \mathfrak{I}^b_t(j) + \Pi^R_t(j) - \Lambda^b_t(j) \right) - \delta_b N^b_t(j) \; . \end{aligned} \tag{27}$$

[15] See also McGuire and von Peter (2009). Stigum and Crescenzi (2007) describe in detail how banks use derivatives to hedge their international operations.

Optimization yields first-order conditions that we show in full, because they reveal important details concerning the structure of spreads. We can drop individual indices because in equilibrium the ratios to net worth of loans, deposits, retail deposit profits and retail lending losses are identical across banks. The expressions $\check{\Omega}^x_{yX,t}$ are the derivatives $\partial\bar{\omega}^b_{t+1}/\partial\check{y}^x_{X,t}$, with $y \in \{\ell, d\}$. We note that the $\check{\Omega}^x_{yX,t}$ are always positive, that they are very similar in size between the two types of wholesale loans and separately between the two types of interbank positions, and finally that they are smaller for interbank positions than for wholesale loans, due to the lower regulatory risk weight on interbank positions.

For domestic currency loans to lenders to domestic households $\check{\ell}^h_{H,t}$ we have

$$\mathbb{E}_t \left\{ r^h_{\ell H,t+1} - r_{w,t+1} - \chi \left[F^b_{t+1} + f^b_{t+1} \check{\Omega}^h_{\ell H,t} \left(\check{\ell}^\ell_t + \check{\ell}^b_{H,t} + e_t \check{d}^b_{F,t} \right) \right] \right\} = 0 \; . \tag{28}$$

This condition contains a *regulatory spread* $\chi \left[F^b_{t+1} + f^b_{t+1} \check{\Omega}^h_{\ell H,t} \left(\check{\ell}^\ell_t + \check{\ell}^b_{H,t} + e_t \check{d}^b_{F,t} \right) \right]$ between the wholesale lending and wholesale deposit rates, whereby the wholesale lending rate must compensate wholesale banks for the fact that that at the margin an additional loan increases the penalty payable in case of a breach of MCAR. The size of this spread depends on a combination of the size of the MCAR (ΘS^{lev}_t), the penalty payable in case of a breach of the MCAR (χ), and the likelihood of a breach given the riskiness of individual banks (F^b_{t+1} and f^b_{t+1}).

For domestic currency loans to lenders to foreign households $\check{\ell}^f_{H,t}$, we have

$$\mathbb{E}_t \left\{ r^f_{\ell H,t+1} - r_{w,t+1} - s^b_t/\pi^p_{t+1} - \chi \left[F^b_{t+1} + f^b_{t+1} \check{\Omega}^f_{\ell H,t} \left(\check{\ell}^\ell_t + \check{\ell}^b_{H,t} + e_t \check{d}^b_{F,t} \right) \right] \right\} = 0 \; . \tag{29}$$

This condition contains a regulatory spread that is virtually identical in size to that for loans to domestic households. But in addition there is an *interbank monetary spread* $\left(s^b_t/\pi^p_{t+1}\right)$, which arises because an increase in exposures to foreign households must be matched with a costly increase in foreign currency interbank deposit balances.

For domestic currency loans to foreign banks $\check{\ell}^b_{H,t}$ we have

$$\mathbb{E}_t \left\{ r^b_{\ell H,t+1} - r_{w,t+1} - \chi \left[F^b_{t+1} + f^b_{t+1} \check{\Omega}^b_{\ell H,t} \left(\check{\ell}^\ell_t + \check{\ell}^b_{H,t} + e_t \check{d}^b_{F,t} \right) \right] \right\} = 0 \; . \tag{30}$$

In this case the regulatory spread is significantly smaller, due to a lower Basel risk weight on interbank loans.

For foreign currency deposits at foreign banks $\check{d}^b_{F,t}$ we have

$$\mathbb{E}_t \left\{ r^b_{dF,t+1} - r^b_{\ell F,t+1} - s^{b\prime}_t \check{\ell}^f_{H,t}/\pi^p_{t+1} - \chi \left[F^b_{t+1} + f^b_{t+1} \check{\Omega}^b_{dF,t} \left(\check{\ell}^\ell_t + \check{\ell}^b_{H,t} + e_t \check{d}^b_{F,t} \right) \right] \right\} = 0 \; . \tag{31}$$

Due to FXMR, foreign currency interbank loans at the rate $i^b_{\ell F,t}$, rather than domestic wholesale deposits at the rate $i_{w,t}$, are the marginal source of refinancing foreign currency interbank deposits. The regulatory spread is virtually identical in size to that of domestic currency interbank loans. In equilibrium this spread is however more than offset by the *interbank monetary discount* $s^{b\prime}_t(\check{\ell}^f_{H,t}/\pi^p_{t+1}) < 0$. The reason for this discount is that holdings of foreign currency interbank deposits reduce the cost of exposures to foreign households.

3.6.2. Retail Deposit Banks

Retail deposit banks have unit mass and are indexed by j. They set the terms of retail deposit contracts. Retail deposit banks place domestic currency wholesale deposits in the money market through financial investors, and pay for them by issuing retail deposit varieties in domestic currency, which are denoted by $D^h_{H,t}(j)$ and $D^f_{H,t}(j)$. Retail deposit banks behave as monopolistic competitors towards the holders of their retail deposits, who demand CES composites of all deposit varieties. This implies the pricing rules for deposits

$$i^x_{dH,t} = \mu^x_{dH} i_{w,t} \quad , \quad x \in \{h, f\} \ , \tag{32}$$

with markdown terms $\mu^x_{dH} \leq 1$. Retail deposit banks are fully owned by wholesale banks, and their aggregate real profits $\check{\Pi}^R_t(j)$ are transferred lump-sum to the latter.

3.6.3. Retail Lending Banks

Retail lending banks set the terms of retail loan contracts, based on a modified version of the costly state verification setup of Bernanke et al. (1999), henceforth BGG. There are two retail lending bank sectors, for loans to the domestic and foreign household sectors, who each have unit mass and are indexed by j. Retail lending banks are homogenous, and each bank lends the same amount to a borrower j. For a domestic borrower j, the total eligible collateral for loan contracts is the gross return to capital $\mathbb{E}_t Ret_{k,t+1} Q_t k_t(j)$, while actual collateral is determined by the fractions $\kappa^h_H S^{cred}_t$ and $\kappa^{h^*}_F$ of this collateral that can be pledged to domestic and foreign banks to obtain loans.

Domestic and foreign retail borrowers from domestic retail lending banks are subject to idiosyncratic productivity shocks $\omega^x_{H,t+1}$, $x \in \{h, f\}$, that are log-normally distributed with mean 1 and variance $(\sigma^x_H)^2$. We denote the pdf and cdf of these shocks by $f^x(\omega^x_{H,t+1})$ and $F^x(\omega^x_{H,t+1})$ and the cutoff productivity shocks below which bankruptcy occurs ex-post by $\bar{\omega}^x_{H,t}$, and we define $f^x_{H,t} = f^x(\bar{\omega}^x_{H,t})$ and $F^x_{H,t} = F^x(\bar{\omega}^x_{H,t})$.

Domestic retail lending banks' cost of funding is given by wholesale lending rates $i^x_{\ell H,t}$, while their loan contracts stipulate non-contingent retail lending rates $i^x_{rH,t}$ on loans $L^x_{H,t}(j)$ that must be paid in full if the realization of the idiosyncratic productivity shock is sufficiently high to avoid bankruptcy. Borrowers decide to declare bankruptcy if their individual productivity shock remains below a cutoff $\bar{\omega}^x_{H,t}$, where handing over the entire value of their project to the bank becomes preferable to realizing the project and repaying the loan. We omit the closed form expression for the equilibrium cutoff $\bar{\omega}^x_{H,t}$ to conserve space. In case of bankruptcy, because of monitoring costs, the bank can only recover a fraction $1 - \xi^x_H$ of collateral, where ξ^x_H is the loss-given-default percentage. The participation constraints for retail loans state that expected wholesale returns must equal the sum of expected gross interest on fully repaid loans weighted by the probability of full repayment, plus the value of pledged collateral net of monitoring costs recoverable in case of default. After some algebra, these constraints can be rewritten in the form of (11) above, which states that ex-ante net loan losses must equal zero. Ex-post net loan losses are generally different from zero because lending rates are non-contingent. Retail lending banks are fully owned by wholesale banks, and their net aggregate loan losses $\check{\Lambda}^b_t(j)$ are transferred to the latter in a lump-sum fashion.

3.7. Cross-Border Financial Markets

Domestic and foreign households and banks are linked through cross-border balance sheet positions and interest rates. For Home, the nominal interest rates on foreign currency loans and deposits are identical to those prevailing in Foreign, $i^x_{\ell F,t} = i^{x*}_{\ell F,t}$ and $i^x_{dF,t} = i^{x*}_{dF,t}$, where $x \in \{h, b\}$. The corresponding cross-border balance sheet positions are $\check{\ell}^x_{F,t} = \check{\ell}^{x*}_{F,t}\frac{1-n}{n}$ and $\check{d}^x_{F,t} = \check{d}^{x*}_{F,t}\frac{1-n}{n}$. Analogous relationships hold for Home currency exposures in Foreign, as well as for CBDC exposures and CBDC interest rates.

3.8. Monetary and Fiscal Policy

3.8.1. Monetary Policy - Taylor Rule

The interest rate on central bank reserves i_t remains a key policy tool of the central bank. We follow common practice in business cycle models in that we do not explicitly model the market for central bank reserve deposits, and instead assume that the rate paid on these deposits determines the rate paid on wholesale money market deposits $i_{w,t}$:[16]

$$i_{w,t} = i_t \ . \tag{33}$$

The Taylor rule for the interest rate on reserves is a conventional inflation forecast-based interest rate rule, with a steady state nominal interest rate $\bar{\imath}$ that is derived from financial investors' steady state first-order condition for wholesale money market deposits. The rule features interest rate smoothing, a countercyclical response to deviations of one-quarter-ahead[17] inflation from the inflation target $\bar{\pi}$, a countercyclical response to deviations of quarter-on-quarter real GDP growth from trend, and an iid monetary policy shock S^{int}_t:

$$i_t = (i_{t-1})^{i_i}\, \bar{\imath}^{(1-i_i)} \mathbb{E}_t \left(\frac{\pi^p_{t+1}}{\bar{\pi}}\right)^{(1-i_i)i_\pi} \left(\frac{g\check{d}p_t}{g\check{d}p_{t-1}}\right)^{(1-i_i)i_y} S^{int}_t \ . \tag{34}$$

3.8.2. Monetary Policy - CBDC Rule

Overview In interpreting CBDC policy rules, a key observation is that, holding constant interest rates on alternative financial assets, a higher interest rate on CBDC is associated with an increased stock of CBDC along with a lower CBDC convenience yield. A higher interest rate on CBDC is therefore expansionary, rather than contractionary as in the case of the interest rate on reserves. This contradicts the frequently heard suggestion that the presence of CBDC would make expansionary policy through lower interest rates easier to implement. Expansionary policy requires higher, not lower, CBDC interest rates.

[16] **?** and Burlón et al. (2022) pay more attention to the modelling of the central bank balance sheet and the domestic interbank market.

[17] This follows Christiano et al. (2014).

As with any monetary instrument, CBDC policy rules can be either quantity rules or interest rate rules (or both), and they can respond countercyclically to different macroeconomic variables. This paper will study a number of possibilities for such rules. All of our proposed rules permit countercyclical responses to either inflation or credit. Subject to this, rules can be classified (shorthand terms in brackets) as quantity rules (Q), interest rate rules (INT), reserves rules (RES), or cash-like zero-interest CBDC (CASH).

CBDC Quantity Rule Under CBDC quantity rules, the Taylor rule for the interest rate on reserves (34) remains in effect, while the central bank fixes the ratio of CBDC to GDP at a target of $\bar{m}^{rat}$ over the cycle, and may also permit it to vary countercyclically:

$$m_t^{rat} = \bar{m}^{rat} - 400\mathfrak{m}_\pi \mathbb{E}_t \ln\left(\frac{\pi_{t+1}^p}{\bar{\pi}}\right) - 100\mathfrak{m}_{cred} \ln\left(\frac{\ell_{H,t}^h}{\bar{\ell}_H^h}\right) . \tag{35}$$

Here $m_t^{rat} = 100\left(m_t/\left(4gdp_t\right)\right)$, $m_t = m_{H,t}^h + m_{H,t}^f$, $\mathfrak{m}_\pi \geq 0$, and $\mathfrak{m}_{cred} \geq 0$. The baseline version of this rule, with $\mathfrak{m}_\pi = \mathfrak{m}_{cred} = 0$, implies a fixed quantity of CBDC relative to GDP, so that any changes in demand for CBDC will be reflected in the interest rate on CBDC $i_{m,t}$ alone, except to the extent that they affect GDP. With $\mathfrak{m}_\pi > 0$ or $\mathfrak{m}_{cred} > 0$, in an inflationary boom or a credit boom this rule removes CBDC from circulation, through a central bank sale to the private sector of government securities against CBDC. This decrease in *money balances* has countercyclical effects that go beyond the effects of the policy rate i_t, which operates through *intertemporal substitution*. The resulting shortage of purchasing power triggers increases in the effective prices of consumption and production in (14) - (17), and increases in convenience yields in (18) and other asset demand equations. The inflation response calls for a $\mathfrak{m}_\pi$ percentage point decline in CBDC-to-GDP in response to a 1.0 percentage point increase in the annualized inflation gap, while the credit response calls for a $\mathfrak{m}_{cred}$ percentage point decline in CBDC-to-GDP in response to a 1.0% increase in the credit gap.

CBDC Interest Rate Rule Under CBDC interest rate rules, the Taylor rule for the interest rate on reserves (34) remains in effect, while the central bank varies the nominal interest rate paid on CBDC relative to the nominal interest rate on reserves, and may also permit it to vary countercyclically:

$$i_{m,t} = \frac{i_t}{\mathfrak{sp}}\left(\frac{\pi_{t+1}}{\bar{\pi}}\right)^{-\mathfrak{m}_\pi}\left(\frac{\ell_{H,t}^h}{\bar{\ell}_H^h}\right)^{-0.05*\mathfrak{m}_{cred}} S_t^{mint} . \tag{36}$$

The baseline version of the rule (36), with $\mathfrak{m}_\pi = \mathfrak{m}_{cred} = 0$, implies a fixed spread $\mathfrak{sp} > 1$ of the policy rate relative to the CBDC interest rate, so that any changes in demand for CBDC will be reflected in the quantity of CBDC m_t alone, except to the extent that they affect the policy rate. With $\mathfrak{m}_\pi > 0$ or $\mathfrak{m}_{cred} > 0$, in an inflationary boom or a credit boom this rule *lowers* the interest rate on CBDC *relative* to the policy rate. This, ceteris paribus, makes CBDC less attractive, so that agents will exchange it for government bonds. This endogenous reduction in CBDC balances has the same effects as the direct withdrawal of CBDC balances under the countercyclical quantity rule. The inflation response calls for a $\mathfrak{m}_\pi$ percentage point increase in the spread in response to a 1.0 percentage point increase in the inflation gap, while the credit response calls for a $0.2 * \mathfrak{m}_{cred}$ percentage point increase in the spread in response to a 1.0% increase in the credit gap.[18] The

[18] This scaling of the response coeffient turns out to be convenient in our quantitative analysis.

shock to the CBDC interest rate rule S_t^{mint} will be used to illustrate the differences in transmission channels of conventional monetary policy shocks and CBDC interest rate rule shocks. Cash-like CBDC is a special case of (36) with $i_{m,t} = 1$.

CBDC Reserves Rule Under CBDC reserves rules, the Taylor rule for the interest rate on reserves (34) does not remain in effect because CBDC is implemented as generalized access to central bank reserves. This implies, first, that the interest rate on reserves must be equal to the interest rate on CBDC, and second, that the wholesale deposit interest rate, which unlike reserves/CBDC does not have a convenience yield, disconnects from the interest rate on reserves and is instead determined by the market. We assume that under this regime the central bank maintains a CBDC interest rate rule that resembles the Taylor rule under the other regimes:

$$i_{m,t} = \left(i_{m,t-1}\right)^{i_i} \bar{\imath}_m^{(1-i_i)} \mathbb{E}_t \left(\frac{\pi_{t+1}^p}{\bar{\pi}}\right)^{(1-i_i)i_\pi} \left(\frac{g\check{d}p_t}{g\check{d}p_{t-1}}\right)^{(1-i_i)i_y} S_t^{int} \,. \tag{37}$$

Here the steady state CBDC rate is calibrated, by reference to the CBDC interest rate regime, as $\bar{\imath}_m = \bar{\imath}/\mathfrak{sp}$. Because CBDC and other forms of money continue to be imperfect substitutes, the central bank continues to have access to a second policy instrument, the quantity of CBDC. We assume that the RES quantity rule is the same as (35) above.

3.8.3. Monetary Policy - CBDC Issuance Arrangements

An important practical concern among policymakers and academics has been the perceived risk of a system-wide run from bank deposits to CBDC. It is clearly only system-wide runs that are specific to CBDC, as runs on individual institutions are possible with or without CBDC. A frequent partial equilibrium fallacy is the argument that holders of bank deposits can, for technological reasons, run into CBDC much more quickly than into cash, thereby increasing systemic risk. This does not survive general equilibrium analysis if the only available counterparties are other private-sector agents, in which case the "run" is merely a reallocation of unchanged stocks of deposits and CBDC among different agents. For a system-wide run to be possible, it is therefore necessary that the central bank itself adopts an *issuance arrangement* whereby it accepts bank deposits in payment for CBDC, and also that it adopts a *policy rule* that elastically accommodates large-scale changes in CBDC demand. The central bank thereby potentially becomes a system-wide and ultimately unsecured lender of last resort to the banking system when it "deposits" the checks thus received.

Central banks have never issued central bank money under such arrangements, and Kumhof and Noone (2021) argue that they should not start doing so with CBDC. Instead, that paper advocates core principles that largely eliminate the risk of system-wide runs. The first line of defense is the policy rule, which should feature an adjustable CBDC interest rate that allows the market for CBDC to clear without a need for either large balance sheet adjustments or large movements in the general price level. A quantity rule could completely eliminate runs into CBDC through lower CBDC interest rates, as long as the necessary interest rate can remain within acceptable bounds. And even under an interest rate rule, rate setting could help dampen large fluctuations in CBDC demand.

The second line of defense is the issuance arrangement, which should only unconditionally guarantee central bank issuance of CBDC against eligible securities, principally government securities, whereas it should not guarantee on-demand convertibility of bank deposits into CBDC.[19] Households and firms would still be able to freely trade bank deposits against CBDC in a potentially very large private market, and that private market could still freely obtain additional CBDC from the central bank, at the posted CBDC interest rate and against eligible securities. During normal times the central bank could also choose to be part of this market by trading CBDC against bank deposits, but this would be at its discretion rather than unconditionally guaranteed. The withdrawal of the central bank from that market during times of stress would be the equivalent of a bank holiday during a cash-driven run in a traditional banking system.

Under these issuance arrangements, which will now be made explicit in the model's specification of fiscal policy, a run into CBDC would be a run from eligible assets, specifically government bonds, and not a run from bank deposits.

3.8.4. Fiscal Policy

The consolidated public sector (government plus central bank) budget constraint, in real normalized form, is given by

$$\check{b}_t + \check{m}_t = \frac{r_{b,t}}{x}\check{b}_{t-1} + \frac{r_{m,t}}{x}\check{m}_{t-1} + p_{H,t}\check{g}_t + t\check{r}f_t - \check{\tau}_t \ . \tag{38}$$

Government bonds and CBDC enter in identical fashion, but with the important difference that the interest rate on CBDC is significantly lower than the interest rate on government bonds, due to the convenience yield of CBDC. This budget constraint makes our above argument about issuance arrangements explicit. Specifically, CBDC can only be issued to the public in two ways, through flow transfers from the central bank to the government that help to finance primary deficits, or through stock exchanges of government bonds and CBDC at the central bank. Bank deposits do not enter at all, thereby ruling out an exchange of bank deposits against CBDC, and thereby a system-wide run from bank deposits to CBDC. It would be trivial to augment this budget constraint to allow for discretionary CBDC issuance against bank deposits.

CBDC issuance against government debt can reduce government financing costs in two ways. First, by increasing the share of financing that pays the lower interest rate on CBDC. And second, by reducing the outstanding stock of defaultable government debt and thereby reducing all equilibrium interest rates - see our discussion of the term $\phi_f\left(b_t^{rat} - \bar{b}_{ss}^{rat}\right)$ in the household budget constraint. As argued by Kumhof et al. (2020), government debt is defaultable and is therefore a liability of the government, while CBDC is not defaultable and is not a liability of the government but rather a hybrid instrument that is closer to equity (in the nation) rather than debt.

Government spending is assumed to be exogenous and stochastic. In the pre-CBDC steady state it is set to equal a constant share s_g of GDP, while over the business cycle it follows an ARMA(1,1) process $\ln\left(\check{g}_t/\bar{g}\right) = \rho_g \ln\left(\check{g}_{t-1}/\bar{g}\right) + \epsilon_t^g + \rho_{eg}\epsilon_{t-1}^g$ that allows the model to better match the moments of government spending in the data. Lump-sum transfers $t\check{r}f$ are an exogenous and small constant that is fixed to balance the pre-CBDC steady state budget after calibrating all other spending and tax rates. Lump-sum taxes $\check{\tau}_t^{ls}$ are zero in steady state but can, depending on the fiscal regime, vary over the cycle. Tax revenues are given by

$$\check{\tau}_t = \check{\tau}_t^{ls} + \tau_{c,t}\check{c}_t + \tau_{L,t}\left(1 - \varpi^h\right)\check{w}_t^{wo}h_t + \tau_{k,t}\left(1 - \varpi^k\right)\left(r_{k,t} - \Delta q_t\right)\left(\check{k}_{t-1}/x\right) \ . \tag{39}$$

[19]It can be shown that guaranteed on-demand convertibility of reserves into CBDC would also need to be ruled out, as this could still facilitate system-wide bank runs. See Kumhof and Noone (2021).

A fiscal rule enforces the stability of the deficit-to-GDP ratio

$$gd_t^{rat} = \overline{gd^{rat}} - 100d^{gdp} \ln\left(\frac{g\check{d}p_t}{gdp_{ss}}\right) , \tag{40}$$

where $gd_t^{rat} = gd_{b,t}^{rat} + gd_{m,t}^{rat}$, $gd_{b,t}^{rat} = 100(B_t - B_{t-1})/GDP_t$, $gd_{m,t}^{rat} = 100(M_t - M_{t-1})/GDP_t$, and where allowance is made for automatic stabilizers through the output gap term $ln\left(g\check{d}p_t/gdp_{ss}\right)$. Treating changes in CBDC in identical fashion to changes in government debt in the definition of the deficit is important for fiscal stability, because it prevents large exchanges between CBDC and government debt from destabilizing fiscal instruments. For our shock simulations we will abstract from most fiscal considerations, including both automatic stabilizers and distortionary taxation. We will therefore use (40) with $dgdp = 0$ to endogenize lump-sum taxes $\check{\tau}_t^{ls}$, while keeping all distortionary tax rates constant. But for three parts of our analysis fiscal issues are important. First, for our transition simulation both automatic stabilizers and distortionary taxation matter. We will therefore use (40) with $dgdp = 0.5$[20] to endogenize $\tau_{L,t}$, with auxiliary rules used to move the other distortionary tax rates in proportional fashion

$$\tau_{c,t}/\bar{\tau}_c = \tau_{L,t}/\bar{\tau}_L \quad , \quad \tau_{k,t}/\bar{\tau}_k = \tau_{L,t}/\bar{\tau}_L \ . \tag{41}$$

Second, for our analysis of the effect of automatic stabilizers in optimized simple rule settings, distortionary taxation is not critical, but automatic stabilizers and their interaction with other policy rule parameters are the subject of the analysis. We will therefore use (40) with $dgdp > 0$ to endogenize $\check{\tau}_t^{ls}$. Third, for our analysis of optimal policy, automatic stabilizers are not critical, but distortionary taxation can potentially generate a trade-off between the quantity and the budgetary cost of CBDC. We will therefore use (40) with $dgdp = 0$ to endogenize either $\check{\tau}_t^{ls}$, $\tau_{L,t}$ or $\tau_{c,t}$.

3.9. Market Clearing and Balance of Payments

The market clearing condition for Home goods output is $\check{y}_t = \check{y}_{H,t} + \check{y}_{H,t}^*$. The market clearing condition for Home goods sold in Home takes into account the share $\mathfrak{r}$ of various costs $\check{\mathfrak{I}}_t$ that represents real resource costs rather than lump-sum rebates, so that we have $\check{y}_{H,t} = \check{c}_{H,t} + \check{I}_t + \check{g}_t + \check{v}_t + \mathfrak{r}\check{\mathfrak{I}}_t/p_{H,t}$. Here $\check{v}_t$ is an autocorrelated mean zero inventory demand shock given by $\check{v}_t/\overline{gdp} = \rho_v \check{v}_{t-1}/\overline{gdp} + \epsilon_t^v$. For Home goods sold in Foreign, we have $\check{y}_{H,t}^* = \check{c}_{H,t}^*\left(1-n\right)/n$. The market clearing conditions for hours, capital and CBDC are $H_t = h_t$, $\check{K}_t = \check{k}_{t-1}/x$, and $\check{m}_t = \check{m}_{H,t}^h + \check{m}_{H,t}^f$. Nominal GDP deflated by the CPI price index, and detrended, is given by

$$g\check{d}p_t = \check{c}_t + p_{H,t}\check{I}_t + p_{H,t}\check{g}_t + p_{H,t}\check{v}_t + e\check{x}p_t - i\check{m}p_t \ , \tag{42}$$

where exports are $e\check{x}p_t = e_t p_{H,t}^* \check{c}_{H,t}^* \left(1-n\right)/n$ and imports are $i\check{m}p_t = p_{F,t}\check{c}_{F,t}$. In our simulations this concept of GDP is only used to compute ratios to GDP of other CPI-deflated variables, such as balance sheet ratios. The variable "real GDP" in our charts is instead based on a Fisher index that is consistent with the method used to calculate real GDP by statistical agencies.

[20] Girouard and André (2005) show that typical values for $dgdp$ in industrialized nations are between 0.34 (US) and 0.5 (Europe).

The current account equation, in real normalized terms, is given by

$$\begin{aligned}
&\check{\ell}^{f}_{H,t} + \check{\ell}^{b}_{H,t} + e_t\left(\check{m}^{h}_{F,t} + \check{d}^{h}_{F,t} + \check{d}^{b}_{F,t}\right) - \check{m}^{f}_{H,t} - \check{d}^{f}_{H,t} - \check{d}^{b}_{H,t} - e_t\left(\check{\ell}^{h}_{F,t} + \check{\ell}^{b}_{F,t}\right) \\
&= \frac{1}{x}\left(r^{f}_{\ell H,t}\check{\ell}^{f}_{H,t-1} + r^{b}_{\ell H,t}\check{\ell}^{b}_{H,t-1} + r^{h}_{mF,t}e_{t-1}\check{m}^{h}_{F,t-1} + r^{h}_{dF,t}e_{t-1}\check{d}^{h}_{F,t-1} + r^{b}_{dF,t}e_{t-1}\check{d}^{b}_{F,t-1}\right) \\
&- \frac{1}{x}\left(r^{f}_{mH,t}\check{m}^{f}_{H,t-1} + r^{f}_{dH,t}\check{d}^{f}_{H,t-1} + r^{b}_{dH,t}\check{d}^{b}_{H,t-1} + r^{h}_{\ell F,t}e_{t-1}\check{\ell}^{h}_{F,t-1} + r^{b}_{\ell F,t}e_{t-1}\check{\ell}^{b}_{F,t-1}\right) \\
&+ \check{\Lambda}^{h}_t - \check{\Lambda}^{b}_t + e_t p^{*}_{H,t}\check{c}^{*}_{H,t}\left(1-n\right)/n - p_{F,t}\check{c}_{F,t}\ ,
\end{aligned} \tag{43}$$

where the first line is the net foreign asset position, which consists of ten gross positions. The change in the net foreign asset position equals the sum of net interest payments on the ten gross positions, plus (small) cross-border components of ex-post loan loss rebates to households minus loan losses of banks, plus the trade balance.

3.10. Shocks

For the purpose of our estimation exercise, the model contains a total of 13 shocks, to consumption demand S^c_t, investment demand S^i_t, government spending $\check{g}_t$, inventories $\check{v}_t$, imports S^m_t, monetary policy S^{int}_t, technology S^a_t, goods price markups $S^{\mu_p}_t$, wage markups $S^{\mu_w}_t$, credit supply S^{cred}_t, bank leverage S^{lev}_t, and money demand S^{mon}_t in Home, and currency demand $S^{ccy^*}_t$ in Foreign.

3.11. Welfare

We evaluate the welfare consequences of different combinations of policy rule parameters for the interest rate on reserves, the interest rate on CBDC, and the fiscal deficit. Welfare is computed as the Lucas (1987) compensating consumption variation (CCV) relative to a baseline with a specific (common but necessarily arbitrary) parameterization of policy rules. Welfare surfaces, which show the CCV for a grid of policy rule parameter combinations, allow us to visualize the effects of different rule settings. We evaluate second-order approximations of Home household lifetime utility and of the model's competitive and Ramsey equilibria using Dynare. Specifically, we evaluate $\check{\mathcal{W}}_t = \check{u}_t + \beta_{hh}\check{u}_{t+1}$, where $\check{u}_t = S^c_t\left(1-(\nu/x)\right)\log\left(\check{c}_t - (\nu/x)\,\check{c}_{t-1}\right) - \psi h^2_t/2$.

4. Calibration and Estimation

The baseline specification of the pre-CBDC economy is a symmetric 2-country model with $n = 0.5$. We assign numerical values to model parameters in two steps. First, we calibrate the parameters that govern the steady state of the model, based on a combination of guidance from the literature and sample averages for the period 1990Q1-2019Q4. Second, we perform Bayesian estimation of the parameters and shock processes that govern the dynamics of the model, based on US data for 1990Q1-2019Q4. Both calibration and estimation impose symmetry between Home and Foreign.

4.1. Calibration

A full listing of all calibrated parameters for the real sector, the financial sector, and the CBDC block, is reported in Tables 1, 2 and 3.

4.1.1. Real Sector

Trend productivity growth is calibrated at 2% in annual terms, $x = 1.005$. The CPI inflation target $\bar{\pi}$ and the (pre-CBDC) equilibrium real interest rate $\bar{r}$ are set to 2% and 3% in annualized terms, respectively, the latter by adjusting the discount factor of financial investors β_{fi}. For preferences, following Christiano et al. (2014), we fix the elasticity of labour supply at 1, and we normalize steady state labour supply to 1 by adjusting the preference weight ψ. The elasticity of substitution between domestic and foreign goods is set to $\theta_c = 1.5$, a common value in the business cycle literature. For technologies, steady state price and wage gross markups are fixed at $\bar{\mu}_p = \bar{\mu}_w = 1.1$, in line with much of the literature. The share of transactions and adjustment costs that represent real resource costs is set to $\mathfrak{r} = 0.5$.

For national accounts ratios, to match BLS sample averages for the US business sector, we set the steady state labor income share to 59.4% by adjusting the share parameter α. We set the ratio of investment to GDP to its sample average of 17.3% by adjusting the depreciation rate Δ. The steady state share of government spending in real GDP is set to its sample average of 19% by adjusting s_g. We set the steady state import share to 14.0% to match its sample average, by adjusting the goods market home bias parameter b^c. We calibrate the capital-to-GDP ratio, which according to Fed and NIPA data equals around 240%, by adjusting the steady-state willingness-to-lend parameter for domestic currency loans κ_H^h.

For fiscal accounts, the steady state government debt-to-GDP ratio is set to its sample average of 75% by adjusting $\overline{gd^{rat}}$. To calibrate the steady-state tax rates we follow the methodology of Kumhof et al. (2021), using detailed NIPA data for the period 2010-2018 to allocate different parts of US tax revenue to six different tax categories, including importantly taxes on land. To match their results, we set marginal rates directly as $\bar{\tau}_L = 0.2508$, $\bar{\tau}_k = 0.3444$, and $\bar{\tau}_c = 0.0342$, and we adjust the tax exemption parameters ϖ^h and ϖ^k to obtain labor and capital income tax ratios to GDP of 11.22% and 3.46%. Given these calibration targets, net lump-sum transfers are adjusted to balance the budget in the initial steady state, and are thereafter held constant relative to steady state GDP.

4.1.2. Financial Sector

The first subset of financial sector calibration targets relates to bank capital ratios. The steady state capital adequacy ratio Θ is set to 10.5% which is the sum of the 8.0% Basel III total capital ratio and the 2.5% capital conservation buffer (see Basel Committee on Banking Supervision (2017)). We omit the countercyclical and GSIB buffers, and the additional supervisory requirements, as these do not apply to all banks and/or at all times. As shown in Federal Reserve Bank of New York (2018), banks hold capital considerably above the regulatory minimum. In our model they do so to self-insure against the risk of violating the MCAR. Based on the data in Federal Reserve

Bank of New York (2018), we therefore set the actual steady state capital ratio to 15.5%, for an endogenous capital buffer of 5.0%, by adjusting banks' dividend payout parameter δ^b.

The second subset of financial sector calibration targets relates to regulatory non-compliance rates of banks and bankruptcy rates of their borrowers. The cumulative share of banks that violate the Basel minimum in any quarter is F^b. We set this share to 2.5% in steady state, close to the approximate historical frequency of systemic banking crises in Jorda et al. (2011), by adjusting the bank riskiness parameter σ^b. Bankruptcy rates of domestic and foreign bank borrowers F_X^x are set to 1.5% in steady state by adjusting the loss-given-default parameters ξ_X^x. This matches the findings of Ueda and Brooks (2011) for non-financial listed US companies, and also approximately matches the historical average of per-capita default rates reported in Albanesi et al. (2017).

The third subset of financial sector calibration targets relates to steady state interest rates and spreads. See Figure 2a for a visual representation. The system is anchored by calibrating the equilibrium real interest rate $\bar{r}$ at 3%, by adjusting the discount factor of financial investors β_{fi}. We set the spread between the policy rate and the rate on government securities to 20 basis points, equal to the sample average of the difference between the Federal Funds rate and the 3-month treasury bill rate, by adjusting financial investors' bonds-in-the-utility function parameter γ. We set the steady state spread between the interbank lending rate and the policy rate to 25 basis points, equal to the average spread between the 3-month LIBOR and the Federal Funds rate over the sample period, by adjusting the parameter ζ, the Basel risk weight on interbank claims. The implied risk weight is $\zeta = 0.28$. The steady state domestic currency interbank deposit rate equals the wholesale deposit rate.

To calibrate wholesale lending spreads, we use a 2000-2016 data set produced by Anderson and Cesa-Bianchi (2020) of "maturity-adjusted credit spreads" (MACS) for listed non-financial US firms. These are spreads between the cost of borrowing for a given firm and an equal-maturity risk-free interest rate. We recall that in the model the wholesale lending rate corresponds to the interest rate that would be charged to a notional zero-risk corporate borrower. A model-consistent calibration for wholesale lending spreads is therefore the spread between the average commercial paper rate paid by the safest blue-chip (AAA) non-bank corporates and the treasury bill rate (not the policy rate) at matching maturities of 3 months. Over the sample period this equals 66 basis points, and we therefore calibrate the wholesale lending rate charged to domestic households to 3.46% by adjusting the MCAR parameter χ. The wholesale lending spread charged to foreign households also contains a regulatory spread of 66 basis points, but in this case there is an additional small MONFX spread. We calibrate this at 10 basis points by adjusting the willingness-to-lend parameter for loans to foreign households κ_H^f. The total foreign household wholesale rate therefore equals 3.56%.

External finance premia or retail lending spreads, which are the spreads between the retail and wholesale lending rates, are calibrated by adjusting the borrower riskiness parameters σ_H^h and σ_H^f. For their data counterpart we use the difference between Moody's seasoned Baa corporate bond yield and the market yield on U.S. treasury securities at 10-year constant maturity. Over the period 1990-2019 this spread equals 189 basis points, which we use to calibrate the retail lending spread on domestic household loans. This yields a domestic household retail lending rate of 5.35% . The retail lending spread on foreign household loans is calibrated at 35 basis points less, so that the foreign household retail lending rate equals 5.10%. The lower retail spread for foreign relative to domestic household loans is justified by the fact that foreign loans are taken out by larger corporates that are more creditworthy than the average domestic currency borrower.

Turning to liability-side rates, the steady-state spreads between the policy rate and retail deposit rates are calibrated by adjusting the spread parameters μ_{dH}^{h} and μ_{dH}^{f}. Pre-GFC average spreads between the US policy rate and the effective interest rate on household checking accounts (from FDIC data) equalled around 300 basis points.[21] However, in our model deposits include a much wider range of financial sector liabilities, including deposits which attract rates much closer to the policy rate. To approximate the average convenience yield of total financial sector liabilities to non-banks, we therefore calibrate this spread at 150 basis points. This is similar to Ashcraft and Steindel (2008), who compute, for the single year 2006, a spread of 134 basis points between the average rate of US commercial banks' portfolio of treasury and agency securities on the one hand and the average rate on their complete portfolio of liabilities on the other hand.

The fourth subset of parameters determines the steady state size and composition of balance sheets. See Figure 2b for a visual representation. Based on US Flow of Funds data for the sample period, retail loans to domestic households are calibrated at 120% of GDP, by adjusting the discount factor of households β_{hh}, while retail loans to foreign households are calibrated at 15% of GDP, by adjusting the parameter φ_b of the interbank money demand function.[22] The ratio of domestic retail deposits held by foreign households is set to a matching 15% by adjusting the currency home bias parameter b^o. The steady state ratios to GDP of consumption and production deposits are calibrated at 53% and 12% based on their average values over the sample in BIS data, by adjusting the velocity parameters $\varkappa^{ci}$ and $\varkappa^{y}$. We set the ratio of foreign currency cross-border interbank deposits to GDP to 20% by adjusting the parameter ϑ_b of the interbank money demand function, with FXMR ensuring that foreign currency interbank loans also equal 20% of GDP. The same assumption for the foreign economy, together with FXMR, ensures that the ratios of domestic currency interbank deposits and loans also equal 20%. Lane and Milesi-Ferretti (2018), Figure 7, shows that this corresponds approximately to the global average across BIS-reporting banks. The equal currency split is roughly representative of European banking systems, while the US banking system's interbank balances are almost exclusively in terms of US dollars. The foregoing calibrations of steady state asset and liability positions, together with the steady state net worth position implied by the calibration of bank capital ratios, leaves the financial investor wholesale deposits to GDP ratio as a residual, at 32.3% of GDP.

The fifth subset of parameters relates to two of the four key interest elasticities of the model (the remaining two are discussed in subsection 4.1.4). The interest semi-elasticity of financial investors' demand for government bonds is calibrated at a very high $\epsilon_b^{fi} = 250$ by adjusting the portfolio preference parameter ϑ_{fi}. This ensures that for financial investors very large changes in relative holdings of wholesale deposits and government securities require only very small changes, measured in a few basis points, in the spread between the wholesale deposit rate and the rate on government securities. Because financial investors function as market makers for CBDC, this assumption also ensures that the issuance of a large stock of CBDC does not lead to large changes in wholesale interest rates. The elasticity of the real policy interest rate with respect to changes in the government debt-to-GDP ratio is the subject of Laubach (2009), Engen and Hubbard (2004) and Gale and Orszag (2004), who report, for the United States, that each percentage point increase in the debt ratio increases the real interest rate by between 1 and 6 basis points. We calibrate this elasticity conservatively at 2 basis points, which requires setting $\phi_f = 0.00005$.

[21] This spread has been significantly compressed during the ZLB period, but we do not consider this period to be representative of normal conditions in the banking sector.

[22] This is a compromise calibration, in that in the US foreign banks' lending to domestic non-banks equals only around 10% of GDP, while for most other economies this share is materially higher.

4.1.3. CBDC

In the transition simulation, which uses the separable BLMA, all but a few parameters remain identical to those of the pre-CBDC economy. This simulation assumes that the steady-state ratio of Home CBDC to nominal GDP jumps from 0% to 30% overnight, and because CBDC is issued against government debt, the ratio of government debt to GDP jumps from 75% to 45%. These changes are implemented by adjusting $\overline{gd^{rat}}$ and $\bar{m}^{rat}$. No CBDC is issued in Foreign, and Foreign government debt stays at 75% of Foreign GDP. Because the introduction of CBDC entails significant changes in bank balance sheets, we also allow the dividend payout parameters δ^b to adjust to maintain steady state bank capital ratios at 15.5%. Finally, by adjusting the parameter $\eth$ we impose that the Home steady state interest rate on CBDC settles at 50 basis points below the retail bank deposit rate, due to a higher convenience yield. This requires a modest $\eth$ of 1.053.

In the post-CBDC policy experiments, which use the nonseparable BLMA, again all but a few parameters remain identical to those of the pre-CBDC economy. In this case the two economies are symmetric, with both featuring a 45% government debt to GDP ratio and a 30% CBDC to GDP ratio in steady state. We again allow the dividend payout parameters δ^b to adjust to maintain banks' steady state capital adequacy ratios at 15.5%, and we allow $\eth$ and $\eth^*$ to adjust to ensure that in both countries CBDC interest rates settle at 50 basis points below the respective interest rates on retail bank deposits. The economy features three CBDC quasi-share parameters per country, in the case of Home these are $b^m_{H,ci}$, $b^m_{H,y}$ and $b^m_{F,ci}$. We adjust these to fix the ratios to GDP of domestic and foreign currency consumption deposits, and of production deposits, at the same levels that they would reach if a hypothetical alternative economy with separable BLMA transitioned to government debt and CBDC levels equal to 45% and 30% of GDP, respectively.

It remains to discuss the policy rule parameters. In the transition simulation, for the interest rate on reserves we assume a conventional Taylor rule, with no interest rate smoothing $i_i = 0$ and inflation and output growth coefficients of $i_\pi = 1.5$ and $i_y = 0.2$, while for CBDC we assume a quantity rule with $\mathfrak{m}_{cred} = \mathfrak{m}_\pi = 0$.[23] This is identical to the baseline used in the post-CBDC policy experiments. For the fiscal rule, we assume $d^{gdp} = 0.5$, with distortionary taxes used to meet deficit targets. This value ensures that the government helps to speed up the transition to a new higher steady state of GDP through automatic stabilizers.

In the post-CBDC policy experiments, the coefficients of the Taylor rule and the CBDC rule are optimized and compared to the above set of baseline coefficients. For the fiscal rule we mostly assume a balanced budget rule with $d^{gdp} = 0$, and with lump-sum taxes used to meet fiscal targets. The exceptions are the analyses of automatic stabilizers and of optimal policy.

4.1.4. Substitutability Between Monies

In our model, the elasticity of substitution θ_d between bank deposits and CBDC determines the elasticity ϵ^{hh}_m, the percent change in the total amount of CBDC in response to a one percentage point increase in the CBDC interest rate. There is no established literature that directly measures this elasticity, because we have not yet seen a major economy introduce CBDC at scale alongside bank deposits, and hence we do not have data on which to base an assessment. The only data we

[23] This allows us to separately study the effects of the steady state quantity of CBDC, in the transition simulation, and of countercyclical CBDC policy rules, in the post-CBDC policy experiments.

do have are from bank-level empirical studies on the stickiness, or lack of responsiveness to interest rate differentials, of deposits held at different financial institutions.

Using data from major UK banks, Chiu and Hill (2018) find that a 1 percentage point increase in an individual institution's deposit rate is associated with an increase in the total stock of deposits of that institution of only around 0.3% compared to the historical trend. For the US, estimates are typically higher. These studies generally measure the elasticity as the percent change in the market share, rather than the amount of deposits, of an institution in response to a 1 percentage point increase in that institution's deposit rate. But these two concepts are quantitatively very close, because the market share equals the institution's amount of deposits divided by total deposits in the market, and changes in an individual bank's deposit rate generally do not change the size of the market very significantly. Adams et al. (2007) estimate a structural model of consumer choice among depository institutions, using a panel data set that includes most depository institutions and market areas in the U.S. over the period 1990–2001, and find that on average a 1 percentage point rise in the deposit rates of an individual bank increases its market share by 2.44%. Dick (2008) estimates a structural demand model for commercial bank deposit services in order to measure the effects on consumers of changes in bank services due to US branching deregulation between 1993 and 1999, and finds that a 1 percentage point rise in deposit rates increases market shares by between 1.77% and 2.99%. Ho and Ishii (2011) estimate a spatial model of consumer demand on a cross-section of retail banking institutions for the year 2000 and find values of 1.36% on average. Finally, Kuehn (2018) estimates a model of branch entry that allows for spillovers across markets using data from 1990 to 2012 and finds a value of 2.32%.

We see this literature as providing a lower bound of around $\epsilon_m^{hh} = 2.5$. It also strongly suggests that perfect substitutability, or a very high substitutability as in the case of ϵ_b^{fi} above, would be an inappropriate assumption. But on the other hand, there are a number of reasons for believing that substitutability would be higher than between different bank deposits, in particular the universal and easy accessibility of CBDC, and the greater economy-wide salience of CBDC in comparison to the deposit products of individual banks.

When we study the economy's behavior around a steady state where CBDC is present in significant quantities equal to 30% of GDP, we therefore adopt a calibration of $\theta_d = 2$, which can be shown to imply an elasticity of approximately $\epsilon_m^{hh} = 25$. This implies that a one percentage point increase in the spread between the domestic currency CBDC and deposit rates, in other words a change in the steady state of this spread from -0.5% to +0.5%, leads to a 25%, or 7.5% of GDP, increase in CBDC balances. We consider this a reasonable assumption, but of course empirical evidence is at this point not available. Instead we will comment on the sensitivity of our results to this assumption at the end of Section 8.

This post-CBDC economy uses the nonseparable BLMA (8), which features constant returns to scale. In this environment CBDC is assumed to be in adequate supply and competing in retail as well as wholesale markets. By contrast, the initial steady state of the transition simulation features no CBDC. In such an economy a higher substitutability between CBDC and deposits is likely, because CBDC would first be introduced into markets where it is most competitive with deposits. Returns to scale are initially also likely to be higher and later decreasing for the same reason, as during the initial introduction the quantity of CBDC would still be limited and any CBDC that does exist is likely to be at a premium before the market becomes more saturated. For this case we therefore use the separable version of the BLMA (7) with a fairly high elasticity of substitution $\theta_d = 5$, which implies decreasing returns to scale of 0.8, and a correspondingly higher ϵ_m^{hh}.

Finally, the elasticity of substitution between domestic and foreign currency money balances θ_o is calibrated at a slightly lower 1.5, to reflect the fact that in some foreign markets the choice between different currencies is determined by established business practices and thus less sensitive to price than the choice between different mediums of exchange. Kumhof et al. (2020) conduct sensitivity analysis to explore the sensitivity of their results to θ_o, for which there is no established literature.

4.2. Estimation

The objective of our estimation exercise is to obtain a quantitatively realistic baseline for the characterization of the pre-CBDC model's dynamics around the steady state, which will then be used for simulations and welfare analysis of the post-CBDC economy. We use standard techniques in the applied DSGE literature (Christiano et al. (2014)). We conduct our estimation using 4 Monte Carlo Markov Chains (MCMC) for a total of 200000 draws, discarding the first 40% of the draws. Our optimisation algorithm automatically sets the scale parameter of the jumping distribution's covariance matrix in order to obtain an acceptance ratio of around one third.

4.2.1. Data and Shocks

We estimate the model using a parsimonious selection of 11 quarterly US variables over the sample period 1990Q1 - 2019Q4. They include the real growth rates of per capita GDP, consumption, investment, government spending, and wages, the level of per capita hours worked, the PCE inflation rate, deviations of the shadow Federal Funds rate (Wu and Xia (2016)) from trend, the real growth rate of per capita total domestic credit, the BAA corporate bond spread, and a broad measure of the US dollar exchange rate. The data sources are reported in Table 4.[24] We apply the same transformations to the variables in the model and the data.

The model features 13 shocks and 2 measurement errors. We classify 6 shocks as demand shocks, including shocks to consumption demand S_t^c, investment demand S_t^i, government demand S_t^g, inventory demand S_t^v, import demand S_t^m, and monetary policy S_t^{int}. 3 shocks are classified as supply shocks, including shocks to technology S_t^a, price markups $S_t^{\mu_p}$, and wage markups $S_t^{\mu_w}$. 4 shocks are classified as financial shocks, including shocks to credit supply S_t^{cred}, bank leverage S_t^{lev}, money demand S_t^{mon}, and foreign currency demand $S_t^{ccy^*}$. Finally, we include two measurement errors, to price and wage inflation, following Justiniano et al. (2013).

4.2.2. Estimation Results

Our choice of priors and our estimation results are reported in Table 5.[25] We set the prior for the mean of our monetary policy rule smoothing coefficient to 0.5, for the response to inflation to 1.5 and for the response to output growth to 0.2. We estimate monetary policy smoothing at 0.75, the response to inflation at 1.28, and the response to output growth at 0.01. Compared to the literature, our estimates for the monetary policy rule suggest a less aggressive policy. This is a consequence of our sample period, which does not include the high-inflation and aggressively

[24] Our sample size is limited by the pre-1990Q1 data availability of some of these variables.
[25] Wherever possible, we center our priors around values found in the existing literature.

anti-inflationary 1980s, while it does include several years where policy was constrained by the zero lower bound. We set the prior for price adjustment costs at 200, and find a posterior mean of 372[26]. We set the prior mean of the habit coefficient at 0.5 and find a posterior at 0.63, broadly consistent with other empirical estimates. The prior for the investment adjustment cost parameter is set to 0.5, and we find a posterior mean of 0.78. Finally, the prior for the loan adjustment cost parameter is set to 0.00050, and we find a posterior mean of 0.00035. We have found that small but nonzero loan adjustment cost parameters are important for a good fit of the model.

For the shock autocorrelation estimates, we set the prior means of the autoregressive parameters to 0.5. We set a standard deviation of 0.2 for most shocks, and a standard deviation of 0.1 for the less conventional inventory and import demand shocks, which would otherwise exhibit a tendency towards very high autocorrelation. We find that some of the most important shocks exhibit a fairly high first-order autocorrelation of around 0.98-0.99, including shocks to technology, consumption demand, credit supply, and currency demand.[27]

For the shock standard error estimates, we assume inverse gamma distributions. For demand and technology shocks we set the prior means to 0.01 with a wide standard deviation of 1, while for markup shocks and measurement errors we set the prior means a little lower at 0.005 with a standard deviation of 0.5. The estimated standard errors have the expected orders of magnitude. For financial shocks, we take account of the generally much greater volatility of financial variables, especially of balance sheets, and of our comparative lack of knowledge about the size of such shocks, by setting the prior means to 0.1 with a standard deviation of 10. The estimated standard errors are indeed generally much larger for financial shocks, except for money demand shocks.

4.2.3. Variance Decomposition and Historical Decomposition

Table 6 reports the variance decomposition of the historical time series that is implied by the above estimates. We find that financial shocks account for around half of the variance of output and of the main components of aggregate demand (except for government spending, which is exogenous), with supply shocks accounting for well under 10% and demand shocks accounting for the remainder. This is an important result in its own right, and it furthermore contributes to explaining why, in our welfare analysis, we will find that CBDC policies, which work primarily through CBDC's effects on the financial and payments system, can make a significant contribution to stabilizing the economy. The contribution of financial shocks to explaining the variance of inflation is also large, at around 60%. In other words, in this model, inflation is a monetary phenomenon more than half of the time, rather than "always and everywhere" (Friedman). The reason is that financial variables are much more volatile than real variables, while the two are linked through the need for money to conduct transactions. Price movements therefore play an important equilibrating role in response to imbalances between financial and real activity. Financial shocks account for 90% or more of the variance of spreads, credit and the exchange rate. For the exchange rate, foreign currency demand shocks play an overwhelmingly large role (90% of total variance). For spreads and credit, in general all four financial shocks are responsible, but for spreads credit supply and bank leverage shocks play an especially important role (87%, with another 7% accounted for by other financial shocks).

[26] We find that partial indexation does not improve the fit of the model.

[27] The high estimated autocorrelation coefficients of financial shocks echo Drehmann et al. (2012), who find that the financial cycle is a highly persistent process.

Figure 3 reports the historical decomposition of GDP growth and of domestic credit growth (both in deviations from trend). For GDP, we observe the very significant contribution of financial shocks, especially but not only around the time of the 2008 Global Financial Crisis. We also observe that demand shocks account for a much larger share of overall volatility than supply shocks. For credit, we observe that financial shocks are dominant at most times.

5. Transition to an Economy with CBDC

Figure 4 studies the effects of introducing, in period 0 and in Home only, CBDC equal to 30% of GDP, through a purchase of government bonds of the same value at market-clearing prices.[28] We assume that the CBDC supply is thereafter kept at 30% of GDP through a quantity rule (35) with $\mathfrak{m}_{cred} = \mathfrak{m}_{\pi} = 0$. The figure only shows the first 25 years (100 quarters) of the transition. The complete transition to the new steady state takes several decades, mainly because the capital stock takes time to reach its new, and much higher, level. To make the final steady state values visible, they are shown with red dotted lines, while the solid lines show the actual transition paths. We begin our discussion with the long-run effects, then turn to transitional dynamics, and finally we discuss the topic of bank disintermediation due to CBDC.

5.1. Long Run Effects

The policy increases GDP by 5.75% in the long run. On the supply side this is accounted for by increases in capital (+14.9%) and labor (+2.5%), and on the demand side by increases in consumption (+5.4%) and investment (+14.9%). The current account deteriorates slightly due to an increase in imports. These long-run beneficial effects are driven by three main factors: lower real interest rates, lower distortionary tax rates, and lower monetary frictions.

For **real interest rates**, the 30 percentage point drop in the ratio of defaultable government debt to GDP, and its replacement by non-defaultable CBDC (Kumhof et al. (2020)), is associated with a 60 basis points drop in the steady state Home real policy rate, and therefore the wholesale deposit rate, from 3.0% initially to 2.4% in the long run. Wholesale lending rates drop by 60 basis points along with the policy rate, as the increase in bank lending is not accompanied by a significant increase in the riskiness of banks. These drops directly stimulate capital accumulation and output growth, and lower the equilibrium return to physical capital, which drops from 4.89% to 4.57%. The real retail deposit rate remains at a 1.5% discount relative to the wholesale deposit rate, thus dropping to 0.9%. The long-run real CBDC rate is at a 50 basis point discount on the deposit rate, at 0.4% (the nominal CBDC rate therefore equals 2.4%). The real interest rate on government debt, which starts out at 2.8%, only drops by a further 4 basis points relative to the policy rate, to 2.16%, due to the high interest semi-elasticity of financial investors. The latter hold deposits equal to 32.3% of GDP immediately before the introduction of CBDC, 62.3% of GDP immediately thereafter as they trade government debt against CBDC with the government and CBDC against

[28] This assumption is of course only made to keep the exposition of the transition as simple as possible. In the real world, the market would likely become very volatile if a central bank were to buy this quantity of debt overnight rather than over a more extended period. This problem does not arise in the model because government bonds have the same maturity as CBDC and bank deposits, so that their prices remain tightly anchored by policy.

bank deposits with households, and 88% of GDP in the very long run.[29] As a result, banks rely more heavily on wholesale funding, with a sizeable share of retail monetary functions now being performed by CBDC. However, due to the generalized reduction of interest rates throughout the economy, banks' average real funding cost pre-and post-CBDC is virtually identical, at 1.93%.

Bank lending and deposits increase by more than 15% of GDP in the long run, because banks satisfy the increase in demand triggered by strong post-CBDC economic growth, combined with the fact that deposits and CBDC are imperfect substitutes in the BLMA. In terms of levels (relative to trend), deposits increase by 21.5% relative to their pre-CBDC level.

One consequence of stronger loan creation is increased lending risk due to higher loan-to-value ratios. This results in higher borrower risk, and this is only partly moderated by the increase in the real value of collateral due to lower real interest rates. Retail lending rates therefore increase by 56 basis points relative to wholesale lending rates, in other words they only drop by 4 basis points relative to the pre-CBDC economy.

Lower real interest rates have additional effects through lower **distortionary tax rates**. Following the transition, real interest rates on government financing worth 45% of GDP (government debt) drop from 3.0% to 2.4% p.a., while real interest rates on the remaining 30% of GDP (CBDC) drop from 3.0% to 0.4% p.a. (the new CBDC interest rate). The combined budgetary saving amounts to 1.1% of GDP. Furthermore, government spending is assumed to be held constant relative to trend while the economy grows strongly, and in the long run this creates additional budgetary saving of 1.1% of GDP. With the sum of government debt and CBDC remaining constant at 75% of GDP, this means that the long-run ratio of tax revenue to GDP can fall by 2.2% of GDP. The government's use of these gains to fund reductions in distortionary taxes further stimulates economic activity. Because tax rates start from different initial levels and change proportionally, the labour income tax rate drops by 2.8 percentage points in the long run, and the capital and consumption tax rates by 3.8 and 0.4 percentage points, respectively.

The final factor, lower **monetary frictions**, cannot be easily isolated from real interest rate and tax rate effects. This is because part of the gains from lower fiscal tax rates can be attributed to the interest savings on CBDC, which are due to the high convenience yield of CBDC. But in addition, money tax rates enter optimality conditions equivalently to fiscal tax rates. Specifically, in steady state the effective price of consumption equals $(1+\bar{\tau}_c)\,(1+\bar{\tau}_{ci}^{mon})$, and the return to capital (under the simplifying assumption that $\Delta = 0$) equals $\overline{ret}_k = 1 + \bar{r}_k\,(1-\bar{\tau}_k)\,/\,(1+\bar{\tau}_{ci}^{mon})$. We find that the long-run drops in $\bar{\tau}_c$ and $\bar{\tau}_k$ equal 0.0038 and 0.0383, while the drop in $\bar{\tau}_{ci}^{mon}$ equals 0.0044. Also, the drop in $\bar{\tau}_y^{mon}$, which does not have a fiscal analogue, equals 0.0009. Therefore, while the reduction in tax frictions is stronger than that in monetary frictions because of the sizeable drop in capital income taxes, the drop in monetary frictions is nevertheless very significant. This can be restated in terms of the Friedman (1969) rule. The original rule states that, because the marginal cost of producing high-powered money equals zero, the money supply should if possible be expanded to the point where the marginal benefit of money also equals zero. However, in a world where almost all money is created endogenously by the private banking system, the marginal cost of money creation equals the spread between wholesale loan and deposit rates, which must always remain positive because of financial frictions and regulation. The introduction of CBDC, issued independently of the banking system, allows the economy to avoid part of these frictions and move closer to the ideal of the Friedman rule, which explains some of the beneficial effects of CBDC.

[29] Their holdings of government debt equal 75% of GDP immediately before the introduction of CBDC, and 45% of GDP immediately thereafter and in the very long run.

5.2. Transition Effects

During the transition, we observe a sizeable and persistent increase in inflation, which equals almost 3 percentage points immediately after the introduction of CBDC. The main reason is that the full output gains are only realized with a delay, while aggregate demand picks up immediately due to the realization of the associated wealth effects. With the policy rate reacting to inflation, all real interest rates remain elevated for some time despite the reduction in long-run equilibrium rates. One consequence is that the real exchange rate initially appreciates (by around 2.5%), even though it depreciates in the long run (by less than 1.5%) due to the increased quantity – and thus lower convenience yield – of Home currency. Because temporarily higher real interest rates also imply temporarily higher government financing costs, tax rates have to remain above their lower long-run levels for some time in order to satisfy the fiscal rule. This further dampens activity compared to the long run. Nevertheless, both consumption and investment immediately start to grow due to a combination of lower tax rates and lower monetary frictions.

Bank deposits drop by 6% immediately following the introduction of CBDC, but as economic activity and therefore the demand for money increases, they reach their pre-CBDC level again after 6 years, and eventually experience a sustained increase of 21.5% relative to their pre-CBDC level. A more gradual introduction of CBDC would reduce or entirely eliminate the initial drop in bank deposits.

5.3. Bank Disintermediation

A significant part of the recent policy discourse and academic literature has expressed concerns regarding the potential for CBDC-driven bank disintermediation – see the literature review in Section 2.1.1. While we do observe a transitory decline in bank lending in Figure 4, this is not driven by the disintermediation channel as conventionally imagined, and furthermore it disappears completely in the long run, where bank balance sheets expand by more than 15% of GDP, and by 21.5% relative to trend. This is another instance where the modeling of banks as a system of gross financial ledger entries rather than a system of net physical savings flows has a decisive effect on the analytical results.

Figure 4 shows that the stock of CBDC increases by 30% of GDP overnight, matched almost entirely by a drop in domestically held retail deposits. However, this does not mean that deposits are crowded out. Instead, it only represents an exchange of gross positions via the balance sheet of financial investors, whose wholesale deposits increase by 30% of GDP. In the first step, financial investors sell some of their government bonds to the central bank against CBDC. In the second step, households sell some of their retail deposits to financial investors against CBDC. In the third step, financial investors pay their new deposits into wholesale accounts, which replace the retail accounts of households but leave total deposits, ceteris paribus, unchanged.

The only reason why overall deposits do drop on impact is that banks lend less, which in turn is due to the temporary increase in real interest rates, including wholesale lending rates. This reduces both the supply of loans (due to a reduction in collateral values) and the demand for loans (due to intertemporal substitution). The drop in lending and in overall deposits is however only around 6% of GDP. Over time, as wholesale lending rates drop to well below their initial levels, total loans and deposits increase well beyond their initial levels, with the additional deposits mostly held by financial investors. Financial investors do not save at all, so that this is again only a rearrangement of gross financial positions, not a physical crowding in of deposits.

To be clear, we do not argue that the introduction of CBDC cannot, under some circumstances, reduce the quantities of deposits and loans, as indeed it temporarily does in Figure 4. Instead, we argue that any effects of CBDC on bank intermediation are unrelated to the allocation of a stock of physical saving, so that a quantitative model built on that assumption cannot capture either the mechanism or the magnitude of the effects. With physical saving being far less elastically supplied than gross balance sheet positions, that assumption, even assuming low substitutability between bank deposits and CBDC, will bias the results towards finding that CBDC leads to bank disintermediation. On the other hand, in our paper the economic stimulus due to CBDC issuance increases the demand for bank deposits, which can be satisfied through an increase in loans that is especially elastic, because with interest rates eventually dropping below their initial levels, banks are not even crowded out due to higher real lending rates.

6. Optimized Simple Rules

We now study the macroeconomic and welfare effects of different specifications and parameterizations of the Taylor, CBDC, and fiscal rules. The pre-CBDC model is the same as the one used in the previous section, except that lump-sum taxes rather than labor income taxes adjust to balance the budget. This represents an attempt to focus the analysis exclusively on monetary policy. The post-CBDC model is identical to the pre-CBDC model except for the presence of nonseparable BLMA that allow for the presence of CBDC, with both countries assumed to have issued CBDC equal to 30% of GDP. All other structural parameters are kept identical to the pre-CBDC model.

Welfare consequences of different policy rule parameterizations are evaluated by performing grid searches over policy rule parameters that compute, at each node, Dynare second-order approximations of both Home household lifetime utility and the equations characterizing the full two-country competitive equilibrium. The optimized parameter combination is the one that yields the largest compensating consumption variation (CCV) relative to a zero welfare gain baseline with a specific and common parameter combination. Figure 5 illustrates the results by way of CCV surfaces that show two of the policy rule parameters on the x- and y-axes, and the CCV relative to the baseline on the z-axis. All policy rule parameters that are not shown in the graphs are fixed at their optimized levels. The Taylor rule interest rate smoothing coefficient is always optimally zero, $i_i = 0$, and the Taylor rule inflation gap coefficient is capped at $i_\pi = 3.0$ as in Schmitt-Grohé and Uribe (2004), in order to limit interest rate volatility. Subject to this constraint i_π is always found to be optimally equal to 3.0.[30] Furthermore, in CBDC interest rate rules the credit gap coefficient is capped at $\mathfrak{m}_{cred} = 1.0$, in this case to limit the volatility of CBDC interest rates. Subject to this constraint $\mathfrak{m}_{cred}$ is always found to be optimally equal to 1.0.

Table 7 shows, for different specifications of the rules, optimized policy rule parameters and associated welfare gains relative to the pre-CBDC and post-CBDC zero welfare gain baselines. The latter are shown in Row 1 and Row 3 of Table 7, and feature symmetric Taylor rules with $i_i = 0$, $i_\pi = 1.5$ and $i_y = 0.2$, a balanced budget fiscal rule $dgdp = 0$, and in Row 3 symmetric CBDC rules with no response to either inflation gaps or credit gaps $\mathfrak{m}_\pi = \mathfrak{m}_{cred} = 0$. All remaining rows of Table 7, and all subplots of Figure 5, will be explained in the following subsections.

[30] We have verified that further welfare gains beyond $i_\pi = 3.0$ are always small.

6.1. Pre-CBDC Economy

In Figure 5a, the zero welfare gain baseline is the pre-CBDC model, rather than the post-CBDC model as for all other subplots, with a pair of symmetric Taylor and fiscal rules with $i_i = 0$, $i_\pi = 1.5$, $i_y = 0.2$ and $dgdp = 0$. Row 1 of Table 7 shows that the CCV of this pre-CBDC zero welfare baseline relative to the post-CBDC zero welfare baseline equals -2.01%. We then keep the Foreign Taylor rule at this calibration and vary the coefficients of the Home Taylor rule while evaluating Home welfare.[31]

The maximum welfare gain relative to the pre-CBDC zero welfare baseline is 0.51%, so that welfare relative to the post-CBDC baseline is -1.50%, as shown in Row 2 of Table 7. The optimized simple rule has Taylor rule parameters $i_i = 0$, $i_\pi = 3.0$ and $i_y = 0.65$. The welfare surface has a familiar shape, with large but quickly diminishing gains as the inflation gap coefficient is raised from 1.5 to 3.0, and a very flat welfare surface in the direction of the output growth coefficient.

6.2. CBDC Interest Rate Rule with Credit Gap

Figure 5b examines the case of a CBDC interest rate rule with response to a credit gap. As can be seen in Row 4 of Table 7, this type of CBDC rule realizes the largest welfare gains relative to the baseline (1.01%).

The optimized simple rule has Taylor rule and CBDC rule parameters of $i_i = 0$, $i_\pi = 3.0$, $i_y = 0.08$ and $\mathfrak{m}_{cred} = 1.0$. The welfare surface shows that welfare is again sharply increasing in i_π, but there is another sharp increase in $\mathfrak{m}_{cred}$. We can decompose this, in Row 5 of Table 7, into the effects of the Taylor and CBDC rules by examining the intermediate case of $i_i = 0$, $i_\pi = 3.0$, $i_y = 0.08$ and $\mathfrak{m}_{cred} = 0$, the case of a fixed spread between the two interest rates. We find that the Taylor rule accounts for around 55% of improvements over the baseline and the CBDC rule for the remaining 45%. A CBDC policy rule can therefore make a very significant contribution to stabilizing the economy. Row 6 of Table 7 also examines the case of $i_i = 0$, $i_\pi = 3.0$, $i_y = 0.08$ and $\mathfrak{m}_{cred} = 0.5$, in other words the optimized Taylor rule accompanied by a less aggressive CBDC rule. In this case the welfare gain is still very large at 0.77%, and the contribution of the CBDC rule to this gain is a still substantial 25%.

We have also examined the case of a CBDC interest rate rule with response to a credit gap when in addition to the estimated pre-CBDC shocks the model admits a new set of shocks that only become possible in the post-CBDC world.[32] Specifically, shocks to $S_{H,t}^{ccy}$ and $S_{H,t}^{ccy^*}$, which affect the relative demands for Home currency deposits versus Home currency CBDC, both in Home and Foreign, are added to the model with the same (high) persistence but twice the (already large) standard error of the estimated currency demand shocks $S_t^{ccy^*}$. Row 7 of Table 7 shows that the optimized Taylor and CBDC rules, as well as the welfare gains, remain almost identical. The reason is that these are pure portfolio shocks that call for an adjustment of gross balance sheet positions, with only very small effects on the real variables that determine welfare. This result is policy-relevant, because concerns with increased capital flow volatility due to CBDC have been prominent in the policy debate.[33]

[31] In other words, adopting this different baseline in Figure 5a ensures that the lowest CCV shown equals 0% rather than -2.01%.

[32] This welfare surface is omitted from Figure 5 to conserve space.

[33] Some of these concerns could however be less about real variables than about financial stability issues that might

6.3. CBDC Quantity Rule with Credit Gap

Figure 5c, and Row 8 of Table 7, examine the case of a CBDC quantity rule with response to a credit gap. The optimized simple rule has Taylor rule and CBDC rule parameters $i_i = 0$, $i_\pi = 3.0$, $i_y = 0.11$ and $\mathfrak{m}_{cred} = 0.67$. The welfare surface shows that welfare is strongly increasing in i_π, while the gains from increasing $\mathfrak{m}_{cred}$ are much more modest and account for only around 10% of the overall welfare gains. The maximum welfare gain is significantly smaller than in Figure 5b, at 0.63%. A quantity rule is therefore inferior to an interest rate rule.

The theoretical reason for this result is that the interaction between money and the real economy is governed by money-in-advance constraints that put a premium on households being able to flexibly obtain the CBDC that they need to adjust to shocks to the real economy, rather than being constrained by a central bank determined quantity, even if the latter is countercyclical. Furthermore, the optimized interest rate rule is able to take advantage of that flexibility, by responding far more aggressively to credit without causing excessive volatility in the real economy. The quantitative counterpart of this difference between rules is the stochastic mean of the CBDC-to-GDP ratio, which remains fairly close to its deterministic mean under CBDC quantity rules, but becomes significantly larger (and government debt-to-GDP ratios significantly smaller) under CBDC interest rate rules. This is principally driven by shocks to credit supply. As a result, we find that these shocks account for the majority of the welfare difference between CBDC interest rate and quantity rules.

In the context of the historical debate about monetary policy rules, the above is a manifestation and generalization of the well-known result of Poole (1970). In his paper, quantity rules perform worse than interest rate rules when shocks to the demand for (retail) money are quantitatively important, in an environment where the entire (retail) money supply is issued and therefore potentially controlled by the central bank. The generalization starts from the observation that even in the presence of central bank issued CBDC the majority of the (retail) money supply will continue to be issued and controlled by commercial banks. While this does not invalidate the mechanism outlined by Poole (1970), it does weaken it, and it also makes it more complex. Specifically, quantity rules perform worse than interest rate rules when shocks to *excess* money demand are quantitatively important, meaning shocks to the balance between the demand and supply of money. This includes all of our financial shocks, including shocks to the demand for overall money S_t^{mon}, shocks to the demand for money in a specific currency $S_t^{ccy^*}$, and shocks to the supply of bank-created money S_t^{cred} and S_t^{lev}. As we have seen, these shocks are indeed quantitatively important in our model.

6.4. CBDC Interest Rate Rule with Inflation Gap

Figure 5d, and Row 9 of Table 7, examine the case of a CBDC interest rate rule with response to an inflation gap rather than a credit gap. The maximum welfare gain is again significantly smaller than in Figure 5b, at 0.57%. The welfare surface shows that welfare is increasing in i_π, but very slowly decreasing in $\mathfrak{m}_\pi$. As a result, the entire welfare gains are due to the Taylor rule. Responding to inflation in the CBDC rule is therefore inferior to responding to credit.

There are two reasons for this result that will be discussed in more detail in Section 8. First, the response to inflation that is appropriate for most shocks can become pro- rather than countercyclical

not be fully captured by our model.

for some quantitatively important financial shocks. Second, following real demand and credit supply shocks the response of inflation is far more short-lived than the response of credit, which in turn has a similar persistence to real variables. These channels are again principally driven by shocks to credit supply, and as in the previous subsection we find that these shocks account for around three quarters of the welfare difference between CBDC interest rate rules with credit versus inflation gaps, with currency demand shocks accounting for the remaining quarter.

6.5. CBDC Reserves Rule

Figure 5e, and Row 10 of Table 7, examine the case of a CBDC reserves rule. This corresponds to the notion of CBDC as generalized retail access, rather than exclusively commercial bank wholesale access, to central bank reserves. It thereby replaces the notion of reserves and CBDC as two distinct forms of central bank money in the foregoing analysis. However, while the central bank in the pre-CBDC economy has access to only one policy instrument, the interest rate on reserves, in the post-CBDC economy it always access to two policy instruments, even with a CBDC reserves rule. The reason is that, once access to reserves is opened up and they become a retail medium of exchange, they enter the economy as an imperfect substitute for retail bank deposits, rather than a perfect substitute for wholesale interbank deposits.[34] This imperfect substitutability can be exploited by the central bank to use the quantity of CBDC/reserves as a second policy tool, in addition to the interest rate on CBDC/reserves.

To represent the above notion of CBDC reserves rules, our model assumes that the CBDC interest rate responds to inflation (in a similar fashion to the Taylor rule for the interest rate on reserves under other regimes), the quantity of CBDC responds to credit (responding to inflation can be shown to be inferior), and wholesale interest rates cease to be determined by policy and are instead determined by the market.

This policy has clear conceptual drawbacks. First, by controlling an interest rate on a form of money rather than on a risk-free asset, policy gives up direct control over the risk-free interest rate. The latter must now be determined by the market as a markup over the new policy rate, which is paid on a form of money, with the markup determined by the potentially volatile convenience yield of CBDC. Second, both the interest rate on and the quantity of reserves affect the economy through the same money supply transmission channel, and it is therefore not possible to set both of them independently to obtain countercyclical results.

Figure 5e, and Row 10 of Table 7, clearly illustrate these points. Welfare increases in the inflation gap coefficient i_π of the interest rate on CBDC, which is again capped at $i_\pi = 3.0$, with an optimal output growth coefficient of $i_y = 0.37$. But given this, welfare is now decreasing, beyond a very low optimal coefficient of $\mathfrak{m}_{cred} = 0.18$, in the credit gap coefficient. This is because policy is giving up the option of taking advantage of a second policy instrument that works through an independent channel. As a result, the welfare gain is again lower than in Figure 5b, at 0.69%.

[34] This is of course a slightly exaggerated description of the substitutability of wholesale reserves. But it is a realistic and useful abstraction. There is a reason why in typical monetary models a convenience yield on reserves is either abstracted from altogether, or else modeled as being very small.

6.6. Cash-Like CBDC

Figure 5f, and Row 11 of Table 7, examine the case of a cash-like CBDC. This corresponds to the notion of CBDC as a retail medium of exchange, separate from central bank reserves, that pays a fixed nominal interest rate of zero, with the central bank satisfying all demand for CBDC at that rate by issuing it against eligible assets. This case features a different steady state from all other post-CBDC policy regimes in Figures 5b-5e, because this policy fixes the steady state real interest rate on CBDC at -2%.

When compared to alternative regimes with no countercyclicality of CBDC policy rules, such as the baseline rule in Row 3 of Table 7 or the inflation gap rule in Row 9 of Table 7, a cash-like CBDC has one advantage. This is that, with a countercyclical response to inflation of the Taylor rule on reserves, combined with a fixed zero nominal interest rate on CBDC, the opportunity cost of CBDC does exhibit some countercyclicality, albeit in response to inflation rather than credit. At the baseline Taylor rule parameters of $i_i = 0$, $i_\pi = 1.5$ and $i_y = 0.2$, the resulting welfare gain over the baseline rule in Row 3 of Table 7 equals 0.34%. The optimized Taylor rule under a cash-like CBDC, which has coefficients $i_i = 0$, $i_\pi = 3.0$ and $i_y = 0.35$, shows a significantly larger welfare gain of 0.65%, with the difference of 0.31% due to the stabilizing properties of the Taylor rule alone.

6.7. CBDC Interest Rate Rule with Credit Gap and Automatic Stabilizers

Figures 5g and 5h, and Row 12 of Table 7, report results for optimized simple rules that allow variations in not only the Taylor rule and CBDC rule gap coefficients but also in the fiscal rule output gap coefficient $dgdp$. We consider a range $dgdp \in [0.00, 0.34]$, 0.34 being the response coefficient estimated for the US by Girouard and André (2005). We maintain our assumption that lump-sum taxes adjust to satisfy the fiscal rule.

Under this condition fiscal policy would ordinarily not matter because of Ricardian equivalence. However, this does not hold in the presence of CBDC. Specifically, as shown in Figures 5g and 5h, welfare increases strongly not only in i_π and $\mathfrak{m}_{cred}$, but also in $dgdp$. The coefficients of the optimized simple rule are $i_i = 0$, $i_\pi = 3.0$, $i_y = 0.13$, $\mathfrak{m}_{cred} = 1.0$ and $dgdp = 0.34$. The welfare gain over the zero welfare baseline now rises to 1.58%, significantly higher than the best balanced-budget optimized simple rule, which achieves 1.01%.

The reason for this non-neutrality of lump-sum taxes is that deficit spending can now lead to not only increased government debt issuance but also to increased CBDC issuance. In fact, as we will show in Section 8, with an optimized CBDC interest rate rule more than 100% of the deficits can end up being financed through CBDC rather than through debt, and this is stimulative because it relaxes the money-in-advance constraints and reduces the effective prices of consumption and production. This is a manifestation of the Friedman (1948) proposition (see also Galí (2020)) that the most effective countercyclical policy is a money-financed fiscal deficit.

6.8. Counterfactual Simulation

Figure 6 compares the time series of the observed data (blue solid line) and of two counterfactual simulations. The latter use the smoothed shock series and estimated parameters of our estimation exercise, but they use different policy rules. "Optimal without CBDC" (red line with circle markers), is a simulation of the pre-CBDC economy that replaces the estimated Taylor rule coefficients with the optimized simple rule coefficients in Row 2 of Table 7. "With CBDC ($\mathfrak{m}_{cred} = 1$)", shown as a black line with square markers, is a simulation of the post-CBDC economy with a CBDC interest rate rule with credit gap. It replaces the estimated Taylor rule coefficients with optimized simple rule coefficients in Row 4 of Table 7, and it sets the CBDC credit gap coefficient to $\mathfrak{m}_{cred} = 1$.

Figure 6 shows all observable variables except government spending, which is exogenous in the model. It also shows three model variables for which we do not have observed data. First, but only for the second counterfactual simulation, we show the CBDC-to-GDP ratio and the CBDC interest rate, and second, we show gross cross-border banking exposures. The latter is defined as the ratio to Home GDP of the sum of all cross-border retail bank loans and bank deposits. We include this variable because one prominent concern among central bankers has been that the introduction of CBDC could contribute to more volatile cross-border financial flows.

Comparison of the data and the counterfactual simulations shows that both counterfactuals achieve a very significant smoothing of all real variables except for the real wage, whose volatility, along with inflation and credit spreads, remains similar to the data. Comparison of the pre-CDBC and post-CBDC counterfactual simulations needs to bear in mind that while the former achieves a similar smoothing of real variables, it does so firstly around a far inferior steady state (see Table 7), and secondly at the cost of substantially higher policy rate volatility. In the post-CBDC counterfactual simulation, policy rate volatility is in fact even lower than in the data because the second policy tool, the interest rate on CBDC, optimally takes on some of the stabilization functions of the interest rate on reserves.

Furthermore, the post-CBDC counterfactual shows a very substantial smoothing of financial variables, not only relative to the data but also relative to the pre-CBDC counterfactual. The standard errors of annualized exchange rate depreciation (5.7) and of annualized domestic credit growth (2.9) are much lower than in the data (8.4 and 3.8) and in the pre-CBDC counterfactual (5.9 and 4.5). The reduction in the standard error of the ratio to GDP of gross cross-border banking exposures, compared to the pre-CBDC counterfactual, is even more pronounced (7.4 versus 11.2). Part of the reason is that, due to the presence of CBDC, the steady state ratio to GDP of these exposures is only 48.5% post-CBDC versus 60% pre-CBDC. But, in addition, the countercyclical use of the CBDC interest rate greatly reduces their volatility.

In summary, compared to the pre-CBDC economy with optimized simple rules, the post-CBDC economy with optimized simple rules achieves much higher welfare, a similar stabilization of real variables around the steady state at a much lower volatility of the interest rate on reserves, and a much greater stabilization of financial sector balance sheets. As for the international dimension, the volatility of both the exchange rate and cross-border financial flows is significantly lower when CBDC is present and when its interest rate is used countercyclically in response to credit gaps.

7. Optimal Policy and Fully Optimized Simple Rules

Table 8 and Figure 7 summarize the results discussed in this section. Our baseline is the competitive equilibrium of the post-CBDC economy with nonseparable BLMA, Taylor rules, CBDC interest rate rules with credit gaps, and fiscal rules where the fiscal deficit-to-GDP ratio remains constant, and therefore the sum of the steady state government debt-to-GDP and CBDC-to-GDP ratios remains constant at 75%. In Table 8 labor income taxes adjust to balance the budget in Home, while Figure 7 also studies endogenous lump-sum and consumption taxes in Home (Foreign continues to use lump-sum taxes). Our objective is not a comprehensive examination of the overall optimal combination of monetary and fiscal policies, but rather a much narrower examination of the optimal CBDC policy in one country, Home, taking all three policy rules of Foreign, and the Taylor and fiscal rules of Home, as given. In this sense it is similar to our optimized simple rules exercise.

The optimized simple rule for CBDC, which is referred to as "OSR"in Table 8, has two features: first a fixed steady state *spread* between the interest rate on reserves and the interest rate on CBDC that ensures a 30% deterministic steady state CBDC-to-GDP ratio at a 2.4% nominal (0.4% real) CBDC interest rate; and second, a *countercyclical policy*, with a credit gap term that ensures dynamic stability while minimizing fluctuations.

The first feature of the optimized simple rule for CBDC turns out to be suboptimal, in that welfare improves further if we also optimize over the steady state spread. There are two ways of performing this optimization. One is through the optimality conditions of the Ramsey planner when the CBDC policy rule, and therefore the fixed steady state spread, is removed altogether. The other is through a joint grid search over both the dynamic rule parameters and the spread parameter $\mathfrak{sp}$. We refer to the latter as a fully optimized simple rule, or "FOSR". Both the OSR and the FOSR exercises are reported in Table 8, and FOSR in much more detail in Figure 7.

The second feature of OSR, and also of FOSR, is highly effective and hard to match by a Ramsey planner. Specifically, we have found that the Ramsey solution is explosive, and that therefore welfare cannot be evaluated for the stochastic model. As a consequence, we do not report the Ramsey solution in Table 8, but we do briefly comment on the deterministic steady state properties of the Ramsey solution in our discussion below.

In our analysis of the OSR, FOSR, and Ramsey solutions, we hold Foreign rule coefficients at the same baseline values as in all our optimized simple rules experiments, and for OSR and FOSR we restrict $\mathfrak{m}_{cred}$ to a less aggressive maximum value of 0.5, as in Row 6 of Table 7. For the FOSR results we also repeat our optimized simple rule computations for the cases of endogenous labor income taxes and consumption taxes.[35] We find that the optimal Taylor rule coefficients remain unchanged in all cases, at $i_i = 0$, $i_\pi = 3.0$, and i_y very small, with the optimal CBDC rule coefficient at its maximum of $\mathfrak{m}_{cred} = 0.5$. For the Ramsey solution, we hold the Home Taylor rule coefficients at the same values.

Figure 7 shows FOSR welfare changes, on the vertical axis, as a function of changes (relative to the baseline of 2.0%) in the steady state spread between the nominal interest rates on reserves and on CBDC, on the horizontal axis. We show deterministic and stochastic means – the criterion for optimality is the stochastic mean. Under endogenous labor income taxes this exhibits a peak at a steady state real CBDC rate of 1.3% (1.65% under Ramsey), far higher than the OSR value of

[35] Recall that Table 7 only reports results for endogenous lump-sum taxes.

0.4%. Under endogenous consumption or lump-sum taxes it becomes optimal to drive the spread as close as possible to zero, although interest rate volatility increases in this direction and might make extreme versions of this policy undesirable. Nevertheless, the policymaker optimally issues a large stock of CBDC, and while this requires a high interest rate on CBDC, it does not increase, and in fact decreases, the interest cost of the sum of government debt and CBDC. The reason is that, under the assumption of an unchanged budget deficit-to-GDP ratio, a higher stock of CBDC reduces the stock of government debt one for one, and this also reduces the interest rate on government debt. Lower interest costs in turn permit a reduction in taxes. Combined with lower real interest rates, this leads to significant output and welfare gains. In the case of labor income taxes FOSR welfare gains reach a maximum of around 0.15% relative to OSR, as reported in Table 8, and in the case of consumption and lump-sum the potential gains are even larger.

The top half of Table 8 reports the deterministic steady state results for the case of endogenous labor income taxes. The quantity of CBDC rises from 30% of GDP under OSR to 39% under FOSR (45.5% in the Ramsey solution), while government debt drops from 45% of GDP under OSR to 36% under FOSR (29.5% in the Ramsey solution). Relative to OSR, output increases by 1.0% under FOSR (1.6% in the Ramsey solution), and welfare exhibits a small gain of 0.16% (0.27% in the Ramsey solution). The FOSR rule therefore exhibits slightly smaller improvements compared to the Ramsey solution. But it does so without its dynamic stability problems.

The bottom half of Table 8 studies the stochastic means of the OSR and FOSR solutions. We observe that under OSR, and more so under FOSR, the combination of persistent shocks and an aggressive countercyclical response, both through the Taylor rule and the CBDC rule, creates a bias towards lower average government debt stocks associated with lower average interest rates on reserves, and higher average CBDC stocks associated with a smaller spread between the interest rates on reserves and CBDC, than in the deterministic steady state. The welfare gains of FOSR over OSR are however similar to the deterministic steady state. These gains are of comparatively modest size – recall that the maximum gains from optimizing the simple rule with fixed spread equal over 1%.

Our results suggest that our optimized simple rule, and especially the version that also optimizes the steady state spread between the interest rates on reserves and CBDC, represents close to the best solution that a policymaker can realistically achieve. We consider this to be a useful first step towards designing effective CBDC policy rules.

8. Impulse Response Analysis

In this section we present impulse responses to help build intuition for the results. The analysis is divided into six parts. First, we compare exogenous shocks to the interest rates on reserves and on CBDC, to illustrate that these two rates, ceteris paribus, need to move in opposite directions to achieve the same output effect. Second, we compare CBDC interest rate and quantity rules, including optimized countercyclical rules, to study why interest rate rules are more effective. Third, we compare CBDC interest rate rules with credit gap terms and inflation gap terms, to study why credit gap terms are more effective. Fourth, we compare CBDC interest rate and reserve rules, to study why interest rate rules are more effective. Fifth, we compare CBDC interest rate rules without and with fiscal automatic stabilizers, to study why automatic stabilizers are effective even when implemented via lump-sum taxes. Sixth, we briefly comment on the consequences of different degrees of substitutability between bank deposits and CBDC, albeit without providing additional impulse responses. In each case we assume that the fiscal rule is satisfied through variations in lump-sum taxes.

For parts two to four of this analysis, we study a selection of representative one standard deviation contractionary shocks. The investment demand shock is representative of the demand shocks of the model, including the consumption demand shock. Supply shocks are not shown, because they do not account for a very significant share of the model's volatility, see Table 5, and because for these shocks the differences between CBDC rules are small and not decisive for the overall welfare results. We study three financial shocks, domestic money demand shocks, domestic credit supply shocks, and foreign currency demand shocks, because a detailed shock-by-shock welfare analysis reveals that these are key to understanding the transmission mechanism of CBDC. Domestic money demand shocks illustrate that a response to credit gaps, while generally highly beneficial, can become procyclical when credit changes due to changes in the demand for money, rather than in the supply of credit or the demand for goods. However, this shock is not decisive for the overall welfare results. Instead, the welfare level differences between different classes of policy rules (INT, Q, RES, and CASH), and the gradients of the welfare surfaces with respect to the CBDC rules' gap coefficients ($\mathfrak{m}_{cred}$ or $\mathfrak{m}_{\pi}$), are predominantly driven by domestic credit supply shocks and, to a lesser but still significant extent, foreign currency demand shocks.[36]

8.1. Monetary Policy Shocks

Figure 8 compares 100 basis points contractionary shocks, in the post-CBDC model with optimized Taylor and CBDC interest rate rules (Row 4 of Table 7), to either the Taylor rule for the interest rate on reserves (black line) or the CBDC interest rate rule (red line).

The key observation is that a contractionary effect (of roughly equal magnitude on impact) is associated with opposite, ceteris paribus, changes in these two policy rates – a higher interest rate on reserves but a lower CBDC interest rate. The reason is the difference in transmission channels. A higher interest rate on reserves affects primarily the intertemporal marginal rate of substitution, and through this real channel it reduces consumption and investment, with the contractionary effect on the quantity of money a consequence of lower money demand. A lower interest rate on CBDC relative to the interest rate on reserves affects primarily the opportunity cost of holding money, and through this financial channel it reduces the quantity of money, with the contractionary effect on consumption and investment a consequence of lower money supply.

8.2. CBDC Interest Rate Rules versus CBDC Quantity Rules

In each of the following figures the blue dashed line is based on a simulation of the pre-CBDC model with an optimized Taylor rule (Row 2 of Table 7). The black line is based on a simulation of the post-CBDC model with optimized Taylor and CBDC interest rate rules (Row 4 of Table 7). The grey line is based on a simulation of the post-CBDC model with the same Taylor rule coefficients as in the previous case but with a CBDC interest rate rule that maintains a fixed spread relative

[36] In the model, consumption monetary aggregates are four times larger than production monetary aggregates. In the interest of simplicity, the impulse responses therefore report as "Money" only the variable $\check{a}_{ci,t}$, and as "Money Tax Rate" only the variable $\tau^{mon}_{ci,t}$.

to the interest rate on reserves. The red line is based on a simulation of the post-CBDC model with optimized Taylor and CBDC quantity rules (Row 8 of Table 7). The orange line is based on a simulation of the post-CBDC model with the same Taylor rule coefficients as in the previous case but with a CBDC quantity rule that keeps the quantity of CBDC fixed relative to GDP. In what follows, we will occasionally refer to combinations of Taylor rules and CBDC rules as regimes.

To anticipate the main result, an optimized CBDC interest rate rule regime yields higher welfare than an optimized CBDC quantity rule regime because households benefit from being able to flexibly obtain the quantity of CBDC that they need to adjust to changes in the economy. A CBDC interest rate rule provides more of that flexibility than a CBDC quantity rule, because it allows households to freely adjust their holdings in response to shocks. The shocks where this matters most are financial shocks, principally to credit supply and currency demand.

8.2.1. Home Investment Demand Shock

Figure 9 shows that a one standard deviation contractionary domestic investment demand shock S_t^i leads to an approximately 1.5% contraction of investment and a 0.15% contraction in GDP. The resulting decrease in inflation triggers a decrease in the real policy rate that is almost identical across regimes, at around -0.12 percentage points on impact. The difference across regimes is in how CBDC policies complement this response.

The key observation is that lower investment demand implies lower credit demand, so that loans decrease by ultimately up to 0.4% of GDP. The countercyclical CBDC regimes respond to this decrease by providing additional CBDC. Under the optimized quantity rule regime the central bank directly injects additional CBDC, and the market-determined CBDC interest rate adjusts by rising relative to the policy rate. Under the optimized interest rate rule regime the central bank directly raises the CBDC interest rate, and market-determined household holdings of CBDC increase because of its higher relative return. By contrast, the fixed spread and fixed quantity CBDC regimes do not respond to the decrease in loans, with CBDC therefore remaining almost constant relative to GDP. As a result, these regimes do significantly worse at stabilizing real variables than the optimized regimes.

The optimized CBDC rules call for a CBDC interest rate and quantity increase that is more than twice as large under the interest rate rule regime than under the quantity rule regime. As a result, the countercyclical interest rate rule is more effective at stabilizing the economy in response to this shock. In Figure 9 we observe this in a smaller deviation from trend of money, and in a larger drop of the money tax rate. This is the main reason for the different behavior of GDP, hours, and consumption. However, the welfare differences across CBDC regimes for this shock are far smaller than for the main financial shocks. Here it is important to recall that the optimal parameter setting of each rule is not determined by the effectiveness of the response to individual shocks but by the jointly optimal response to all shocks. And while the quantity rule could do better by being more aggressive in response to credit changes triggered by investment demand shocks (or other demand shocks), this would be too costly in response to financial shocks.

In Figure 9, the behavior of retail bank loans is quite similar across regimes, while the behavior of retail bank deposits is quite different. This is due to the mechanics by which households acquire CBDC. Specifically, they interact with financial investors as CBDC market makers, who procure additional CBDC from the central bank against part of their government bond portfolio, and who then sell that CBDC to households against bank deposits. This results in a decrease in (household) retail deposits and an increase in (financial investor) wholesale deposits.

8.2.2. Home Credit Supply Shock

A one standard deviation contractionary shock to domestic credit supply S_t^{cred} causes loans to contract due to lower supply of rather than lower demand for credit, by ultimately more than 3 percent of GDP. But Figure 10 shows that otherwise the differences across policy regimes have a similar pattern as in Figure 9.

The response of the real policy rate is again broadly similar across regimes, with an initial drop of around 25 basis points. Absent a CBDC policy response, the shock triggers a decrease in money and an increase in the money tax rate. As a result, GDP and inflation fall. The fixed spread and fixed quantity CBDC regimes again perform worst at stabilizing the real economy. Under a countercyclical CBDC response to credit the drop in money is smaller. Under a sufficiently aggressive response, as with the optimized CBDC interest rate rule, money quickly starts to increase rather than decreasing, and this eliminates almost the entire output contraction.

There are two key differences between the two optimized CBDC rules. First, the interest rate rule allows households to adjust their CBDC balances far more flexibly. Second, the optimized interest rate rule is able to take advantage of that flexibility, by responding far more aggressively to credit without causing excessive volatility in the real economy. It calls for a response of the CBDC interest rate and quantity that around twice as large than under the optimized quantity rule regime, and is therefore far more countercyclical. As a result, credit supply shocks account for the majority of the welfare difference between CBDC interest rate and quantity rules.

8.2.3. Foreign Currency Demand Shock

Figure 11 shows that a one standard deviation portfolio shift by foreigners from domestic currency to foreign currency $S_t^{ccy^*}$ is contractionary. It leads to a 1.5% impact depreciation of the domestic currency followed by an appreciation over time, so that the relative financial return to the domestic currency must increase along with a decrease in its relative convenience yield.[37] This increase in the domestic real interest rate leads to a contraction in aggregate demand, and thereby in money and credit. In addition, domestic credit decreases due to the drop in demand for domestic currency deposits. With countercyclical CBDC policy rules the central bank counteracts this decrease in credit through an increase in the interest rate on or the quantity of CBDC. This stimulates the economy, so that for the most countercyclical CBDC regime the drop in GDP is smaller, and more quickly eliminated. The two key differences between the optimized CBDC rules were discussed above for the Home credit supply shock. But in this case the optimized interest rate rule calls for a response of the CBDC interest rate and quantity that is roughly equal to the optimized quantity rule regime.

[37] The increase in the financial return to domestic currency in turn causes a switch of domestic households from foreign to domestic currency, which is however smaller than the switch of foreign households.

8.2.4. Home Money Demand Shock

Figure 12 studies a one standard deviation contractionary shock to the demand for money S_t^{mon}. This can be characterized as a domestic "flight to safety" shock, where the safety is that of liquid monetary assets. Domestic households demand more money for any given amount of real activity, and the result is a combination of more money and less real activity. Figure 12 shows that money increases by more than 1.5% while GDP decreases by between 0.10% and 0.15%.

Home money consists of Home bank deposits and Home CBDC, and the two respond differently to the increase in money demand. For bank deposits, because Home households satisfy their money demand predominantly with Home currency assets, one consequence of the shock is an increase in Home banks' retail lending equal to around 1% of GDP. For CBDC, we again need to distinguish between different policy regimes. With a fixed spread CBDC interest rate rule (grey), the Home central bank passively accommodates the increase in demand for Home currency money, by issuing additional CBDC. As a result, this rule is most effective at stabilizing real variables. The second most effective rule is the fixed quantity CBDC quantity rule (orange), where the Home central bank keeps the quantity of CBDC constant relative to GDP. By contrast, with countercyclical CBDC rules the central bank responds to the increase in credit by withdrawing CBDC from the economy, thereby reducing the quantity of money and worsening the contraction. Therefore, for this one shock, a procyclical response to credit would be superior to a countercyclical one, and the usual ranking of policy rules is reversed. However, this result does not dominate the overall welfare results.

8.2.5. Global Run into Home CBDC

A key concern among central bankers has been the potential implications of CBDC for the stability of international financial flows. We have addressed this in our counterfactual simulation by studying the behavior of gross cross-border balance sheet exposures of banks. We address it here by studying the response of the Home economy to an increase in the demand for Home currency CBDC at the expense of Home currency retail bank deposits, by both Home and Foreign households. CBDC demand shocks have of course not been part of our estimation, and we therefore have to choose arbitrary values for the autocorrelations and standard errors of these shocks. As in Row 7 of Table 7, we choose the same autocorrelation and twice the standard error of foreign currency demand shocks. These shocks are therefore extremely large and highly persistent.

Figure 13 shows that, under CBDC interest rate rule regimes (black and grey), the increase in demand for CBDC causes households to sell off retail deposits and buy CBDC. The magnitude of each of these balance sheet changes is around 6% of GDP. However, lower retail deposits do not imply lower overall deposits, because financial investors first exchange government bonds for CBDC (with the central bank), then exchange CBDC for bank deposits (with households), and then hold on to these deposits as wholesale rather than retail deposits. In fact, overall deposits (retail plus wholesale) not only do not decrease, they increase by 0.7% of GDP on impact. The reason is that there is an increase in loan demand due to lower real interest rates and the associated increase in collateral values. In other words, a run from domestic retail bank deposits into CBDC increases, rather than decreases, the size of domestic bank balance sheets, albeit with an increased reliance on wholesale rather than retail funding.[38]

[38] This is another instance where the modeling of the financial system as a system of gross financial ledger entries

The shock is contractionary, mainly because the change in the composition of money increases the money tax rate. The size of this effect is small under CBDC interest rate rule regimes (black and grey), but significantly larger under CBDC quantity rule regimes (red and orange). The reason for the small effects under CBDC interest rate rules is that they passively accommodate the increase in CBDC demand (except for a contractionary response to the increase in bank lending under a countercyclical CBDC interest rate rule), by allowing households to obtain any desired quantity of CBDC against eligible assets at the prevailing interest rate. The reason for the larger effects under CBDC quantity rules is that they do not accommodate the increase in CBDC demand (they even contract CBDC further in response to the increase in bank lending), and instead allow the CBDC interest rate to clear the market at the quantity of CBDC that is fixed by the policy rule, without regard for the increase in demand for Home currency CBDC.

This reinforces the argument in favor of CBDC interest rate rules over CBDC quantity rules. With interest rate rules, a global run into CBDC is mainly a rearrangement of gross balance sheet positions among households, financial investors, banks, and the central bank. Financial investors sell government bonds to the central bank and are paid in additional CBDC,[39] and households buy that CBDC from financial investors and pay using retail deposits. The end result is a switch in the composition of household money, away from retail bank deposits and towards CBDC, and a switch in the composition of bank liabilities, away from retail deposits and towards wholesale deposits. None of this directly involves any real variables, such as international savings.

8.3. CBDC Interest Rate Rules with Credit Gaps versus Inflation Gaps

Each of the following figures is based on simulations of the post-CBDC model with different CBDC interest rate rule regimes. The black line, as above, is based on a simulation of the CBDC interest rate rule with a credit gap and optimized regime coefficients (Row 4 of Table 7). The grey line is based on a simulation of the CBDC interest rate rule with an inflation gap and optimized regime coefficients (Row 9 of Table 7). Finally, the green line is based on a simulation of the CBDC interest rate rule with an inflation gap, with the same Taylor rule coefficients as for the grey line but an excessively, and suboptimally, aggressive CBDC response to inflation, $\mathfrak{m}_\pi = 3$.

We can be brief in our discussion of the economic intuition, because for the case of the CBDC interest rate rule with response to a credit gap (black) all four impulse responses have already been discussed above. For the CBDC interest rate rule regime with an optimized response to the inflation gap (grey), the optimized response coefficient equals 0. This implies that the spread between the CBDC and policy interest rates remains constant, which in turn implies that the ratio of CBDC to GDP remains close to constant. With this rule CBDC is therefore not used for countercyclical policy. The alternative rule with an excessively aggressive response to the inflation gap (green) calls for injections of CBDC when the inflation rate drops, thereby stimulating the economy.

The key observation for investment demand shocks (Figure 14), other demand shocks, and especially credit supply shocks (Figure 15), is that the response of inflation to the shocks is far more short-lived than the shocks themselves and the response of the real economy, and therefore than the response of credit. As a result, the optimized response to inflation performs much worse than the

rather than of physical resource flows is critical. Savings play virtually no role in this shock.

[39] They are unable to do this under a CBDC quantity rule, because the central bank does not issue additional CBDC. Instead, the market-determined CBDC interest rate drops relative to the interest rate on reserves, due to an increase in the convenience yield of CBDC following the shock to CBDC demand.

optimized response to credit, and the aggressively countercyclical response to inflation does not do better, because the countercyclical CBDC response is far too short-lived.

Under currency demand shocks (Figure 16), the large exchange rate depreciation causes the inflation rate to increase, while the drop in demand for domestic currency causes domestic credit to decrease. As a result, a response to inflation is procyclical while a response to credit is countercyclical. This is why the optimized and especially the excessively aggressive inflation gap rules perform far worse. This shock can therefore be shown to be the quantitatively most important driver of the welfare differences between inflation gap and credit gap regimes.

Under money demand shocks (Figure 17), a response to credit is procyclical while a response to inflation is countercyclical. Therefore, for this shock an aggressive CBDC response to inflation is beneficial. However, this result does not dominate the overall welfare results.

8.4. CBDC Interest Rate Rules versus Reserves Rules

In each of the following figures, the black line is again based on a simulation under the optimized CBDC interest rate rule regime (Row 4 of Table 7). The pink line is based on a simulation under the optimized CBDC reserves rule regime (Row 10 of Table 7).

Under domestic investment demand shocks (Figure 18) and other demand shocks, the optimized CBDC interest rate rule regime calls for an interest rate on reserves that decreases in response to a drop in inflation, along with a CBDC interest rate that is raised aggressively over time to incentivize additional holdings of CBDC. By contrast, under the optimized CBDC reserves rule regime, there is almost no countercyclical CBDC response. As a result, the wholesale deposit rate, which is now market-determined, remains at an almost constant spread relative to the CBDC rate, and follows a path that is almost identical to that under the optimized CBDC interest rate rule regime. Because this behavior of real interest rates is critical for an effective countercyclical response through intertemporal substitution, this explains why under this shock the welfare differences between the two regimes are small.

Under domestic credit supply shocks (Figure 19), interest rate and reserves regimes again feature an almost identical initial drop in the real wholesale deposit rate, but very different behavior for the CBDC rate. Under the optimized reserves regime, the primary target of the CBDC interest rate is inflation rather than credit, while the quantity of CBDC responds only very weakly to credit. As a result, the CBDC interest rate is not raised to incentivize CBDC demand, the quantity of CBDC remains almost fixed, money remains lower, and the money tax rate and the convenience yield of CBDC remain higher compared to the interest rate regime. Furthermore, the real risk-free rate does not remain as low for as long, because it is now determined by the market and needs to remain arbitraged with the CBDC rate. All of this contributes to a much larger and more protracted decline in GDP, hours and consumption, and therefore to lower welfare.

Under foreign currency demand shocks (Figure 20), the shock is followed by similar real wholesale deposit rate responses under the two regimes, but by a strong countercyclical injection of CBDC under the interest rate regime, in contrast to a much smaller injection under the reserves regime. The initial contraction of aggregate demand is therefore slightly deeper, and the speed of recovery slightly slower, under the reserves regime.

The key insight is that, with a reserves regime, central bank policy gives up its ability to independently control intertemporal substitution, through the wholesale deposit rate, and the quantity of money, through the CBDC rate. This matters most for financial shocks, which are therefore responsible for most of the welfare losses of reserves regimes relative to interest rate regimes.

Under domestic money demand shocks (Figure 21), as for all previous comparisons of policy regimes, the optimized interest rate rule performs worse than its alternative, because for this shock a reduction of the quantity of CBDC in response to increased credit is procyclical. The reserves rule mostly avoids this problem. But the differences across regimes are small, and this shock is not decisive for the overall welfare outcomes.

8.5. CBDC Interest Rate Rules without versus with Automatic Stabilizers

Figure 22 compares two optimized CBDC interest rate rule regimes with credit gaps. The black solid line is the balanced budget baseline, and the blue dashed line is an alternative regime with automatic stabilizers, with $dgdp = 0.34$. For this alternative we re-optimize the coefficients of the two interest rate rules, and find that i_π and $\mathfrak{m}_{cred}$ remain unchanged while i_y increases slightly from 0.08 to 0.13. For our impulse response comparison we use the consumption demand shock, because it displays the differences across the two regimes most clearly.

In the right columns we now display the ratios to GDP of the government deficit, government debt, CBDC, and the sum of government debt and CBDC. The main difference between the two rules is that with automatic stabilizers the deficit is allowed to rise. Because this deficit takes the form of an increase in lump-sum transfers to households, it does not affect the economy through a change in distortionary tax wedges. But it does affect the economy through a change in the quantity of money. Specifically, any increase in transfers can be financed through issuance of CBDC as well as debt, and any issuance of CBDC stimulates aggregate demand through an increase in the overall quantity of money.

To see that deficit spending must increase both CBDC and debt at least in their previous proportions, assume that the government issues only debt, to financial investors, and gets paid by financial investors with wholesale deposits, which the government spends by making the deficit-triggering lump-sum transfers to households, the deposits therefore ending up as retail deposits in the hands of households. Because households now hold an excessive quantity of retail deposits relative to CBDC, they approach financial investors in their role as CBDC market makers to convert some of their deposits to CBDC. Ceteris paribus, that is at a given CBDC interest rate, the central bank is willing to supply this CBDC against some of the bonds that the government has just issued to financial investors. The central bank ends up with some of the bonds that financial investors use to pay for CBDC, and financial investors end up with some of the deposits that households use to pay for CBDC. Households end up with increased quantities of both deposits and CBDC, and this stimulates the economy.

Under both countercyclical regimes shown in Figure 22, the consumption demand shock causes a drop in the demand for goods and thereby for credit, and CBDC policy responds to lower credit by injecting CBDC. As a result, CBDC must increase by more than in previous proportions. Any increase in CBDC furthermore triggers a feedback loop whereby the demand for deposits and therefore for credit becomes even weaker, and lower credit triggers additional injections of CBDC due to the countercyclicality of the CBDC rule. But when, with automatic stabilizers, deficits are allowed to further increase the quantity of CBDC, this feedback loop becomes much stronger, so that the amount of credit drops by far more, and the amount of CBDC increases by far more, than with a balanced budget rule. Also, under automatic stabilizers the optimal credit gap coefficient is even larger, which further reinforces this mechanism.

In Figure 22, with automatic stabilizers deficits cumulate to produce an ultimate increase in the combined stock of government financing, defined as the sum of government debt and CBDC, of around 1% of GDP over and above the increase observed under a balanced budget rule. However, almost all of this is accounted for by CBDC. The additional CBDC reduces the drop in the quantity of money and thereby in consumption. This explains the welfare gains of this policy that we reported in Section 6.7.

Money-financed fiscal deficits (Friedman (1948)) are therefore highly effective. Furthermore, with CBDC, unlike with cash (or a cash-like CBDC), they are not inflationary. This is because, while with a cash-financed fiscal deficit an injection of money would trigger some combination of higher real activity and a higher price level, with a CBDC-financed fiscal deficit the same injection would trigger some combination of higher real activity and a higher CBDC interest rate, with negligible effects on inflation.

8.6. Effects of Substitutability between CBDC and Bank Deposits

Our calibration assumes that the elasticity ϵ_m^{hh} of CBDC holdings with respect to the spread between CBDC and deposit interest rates equals around 25. This is far from perfect substitutability, but also far from the very low substitutabilities between deposits at different banks that were found by the empirical literature, and that we discussed in Section 4.1.4. In this section we briefly discuss how our results would change if we calibrated ϵ_m^{hh} to be lower, and therefore the complementarity between CBDC and bank deposits to be greater.

In the transition simulation, this change would increase the long-run growth of bank deposits, and through the resulting effects on monetary aggregates also the long-run output gains. In the OSR experiments, it would increase the advantages of interest rate rules over quantity rules. This is because if CBDC was highly complementary with deposits, it would become more critical for households to be able to flexibly choose their CBDC holdings. But at the same time, the countercyclical variations in interest rates that would be required to bring about any desired change in CBDC holdings would become larger, and might take these rates into a range, such as negative rates, that could not be sustained indefinitely, for political reasons. Therefore, in the FOSR experiments, it would become relatively more important for welfare to choose the level of the spread $\mathfrak{sp}$ rather than the countercyclical coefficient m_{cred}.

9. Summary and Conclusions

This paper studies the implications of introducing CBDC into a carefully calibrated and estimated 2-country DSGE environment that features a realistic financial system, and separate policy rules for CBDC and for the interest rate on central bank reserves. CBDC and bank deposits serve as competing and imperfectly substitutable mediums of exchange, and both are globally accessible. The financial sector is modelled as a system of gross financial ledger entries rather than of net physical resource flows. Retail CBDC enters the economy via central bank purchases of government bonds or transfers to the government budget. It is separate from wholesale central bank reserves, and due to its non-pecuniary convenience yield it is remunerated at an interest rate below the interest rate on reserves.

We first carefully calibrate the steady state of the pre-CBDC model, and then estimate its dynamic and policy rule parameters using Bayesian techniques. The key finding is that financial shocks account for around half of the variance of real aggregate demand and inflation, and for the bulk of the variance of financial variables. This suggests that smoothing financial variable fluctuations can make a very important contribution to welfare. This matters because CBDC policies are particularly effective at smoothing financial variables.

We adopt the calibrated and estimated parameters of the pre-CBDC model in a post-CBDC model that is mostly identical, except for the presence of CBDC. We show that the introduction of CBDC equal to 30% of GDP by a single economy is highly beneficial, yielding long run output gains in that economy of just under 6% and long run welfare gains of around 2%. This is because the introduction of CBDC into a large economy like the US can lower real interest rates due to a reduction in the stock of defaultable debt combined with the funding cost advantage of CBDC over defaultable debt, lower distortionary tax rates due to the budgetary space created by lower real interest rates, and lower monetary frictions due to a reduction in tax-like monetary wedges that represent a move of the economy towards the ideal of the Friedman (1969) rule. Bank balance sheets grow significantly in the long run, while banks' average cost of funding remains approximately constant, countering the notion that introducing a CBDC inevitably leads to bank disintermediation.

We optimize and evaluate a number of different simple policy rules for CBDC, alongside a conventional Taylor rule for the interest rate on reserves. We find throughout that, in the Taylor rule, interest rate smoothing is optimally zero, and that the response to inflation should be as aggressive as possible to maximize welfare. This leaves the optimization of the output growth coefficient of the Taylor rule and, more importantly, either the credit or the inflation gap coefficient of a CBDC interest rate rule and/or quantity rule.

For the design of these simple CBDC rules, we find the following results:

1. *Financial rather than real shocks dominate the welfare comparisons between different CBDC rules (while the opposite is true for Taylor rules).* The reason is that the transmission mechanism of CBDC makes it an especially effective tool at smoothing the effects of financial shocks.

2. *In a contractionary episode the CBDC interest rate should, ceteris paribus, increase rather than decrease.* The reason is that increasing the CBDC interest rate relative to the rate on reserves lowers the opportunity cost of holding CBDC. This increases the overall quantity of money and thereby stimulates the economy.

3. *A countercyclical CBDC interest rate rule can partly share the burden of a countercyclical Taylor rule for the interest rate on reserves in stabilizing inflation and output, while also stabilizing financial variables.* The reason is that the CBDC interest rate works through a money supply channel that complements the intertemporal substitution channel of the interest rate on reserves.

4. *CBDC interest rate rules perform better than quantity rules, with the best rule yielding welfare gains of over 1.0% of steady state consumption.* The reason is that shocks to excess money demand are estimated as being quantitatively important. Money-in-advance constraints put a premium on households being able to flexibly obtain the quantity of CBDC that they need when they are exposed to such shocks, rather than being constrained by a quantity that is fixed by the central bank. This flexibility also allows the interest rate rule to be more aggressively countercyclical without causing excessive volatility in the real economy.

5. *CBDC interest rate rules perform better with credit gap terms than with inflation gap terms.* The reason is that the response to inflation that is appropriate for most shocks can become pro- rather than countercyclical for some financial shocks, and also that following real demand and credit supply shocks the response of inflation is far more short-lived than the response of credit and of the real economy.

6. *CBDC reserves rules, or the implementation of CBDC as generalized access to central bank reserves, are inferior to CBDC interest rate rules in welfare terms.* The reason is that with a reserves rule the central bank gives up the ability to independently control intertemporal substitution (through the interest rate on reserves) and the quantity of money (through the CBDC interest rate).

7. *A cash-like zero-interest CBDC is inferior to CBDC interest rate rules in welfare terms.* The reason is that a cash-like CBDC does not allow for countercyclical CBDC policy rules. Also, under even moderately high interest rates the demand for a zero-interest CBDC will be much more limited than the demand for a positive-interest CBDC.

8. *In the presence of a CBDC interest rate rule, automatic fiscal stabilizers become highly effective even if implemented through lump-sum transfers.* This is because when fiscal deficits respond to an output gap, and the CBDC interest rate rule responds to a credit gap, transitory fiscal deficits are optimally financed almost completely through CBDC issuance. This increase in the quantity of money is countercyclical, and achieves even larger welfare benefits than the CBDC interest rate rule that is best under a balanced budget.

9. *The best CBDC interest rate rules can reduce the volatility of real and financial variables very significantly.* While this smoothing of the cycle is similar to what a conventional but aggressive Taylor rule can accomplish in the pre-CBDC economy, the latter does so around a far inferior steady state, and at the cost of substantially higher volatility in policy rates and in financial variables.

10. *A CBDC policy rule that is optimized over its steady state coefficients as well as its dynamic feedback coefficients yields further welfare gains and calls for a high steady state quantity of CBDC.* Specifically, it calls for CBDC at over 40% of annual GDP, remunerated at a high CBDC interest rate.

These results provide useful guidance on the form that CBDC policy rules might take to stabilize output, inflation, and financial markets. The conclusion is quite similar to that reached 30-40 years ago in the debates about the merits of monetarism, which also found that interest rate rules were preferrable to monetary aggregate quantity rules. The difference is that in the case of CBDC the main transmission channel is the financial system. As a result, countercyclical policy is more effective when it responds to a financial variable, in our case domestic credit, rather than to inflation.

Turning to the open economy dimension, we find three main results:

1. *Optimized CBDC policies substantially reduce exchange rate volatility.* This is because they stabilize fluctuations in relative currency demands.

2. *Optimized CBDC policies substantially reduce the volatility of gross cross-border banking balances relative to the pre-CBDC economy with an optimized Taylor rule.* This is partly because the presence of CBDC reduces these balances in steady state, but more importantly because the countercyclical use of the CBDC interest rate reduces their volatility.

3. *Even very large shocks to the demand for a country's CBDC have small real effects, and can be accommodated through benign balance sheet reallocations.* This is because such shocks primarily trigger reallocations in gross balance sheet exposures rather than in saving. Effects are especially benign when CBDC is supplied flexibly by the central bank, subject to an interest rate rule.

These results provide further useful guidance on the effects of CBDC policies in open economies that are exposed to both global and local shocks. They should alleviate some of the concerns that policymakers have recently expressed regarding the potential for CBDC to cause instability in globalized financial markets.

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Table 1. Calibration: Real Sector Steady State

Description	**Calibration Target**	**Parameter Symbol**	**Parameter Value**
	Miscellaneous		
Share of Home in World Economy	50%	n	0.5
Real Growth Rate	2% p.a.	x	1.005
Inflation Rate	2% p.a.	$\bar{\pi}$	1.005
Real Policy Interest Rate	3% p.a.	β_{fi}	0.9975
Labor Supply Level	1	ψ	0.588
EoS Home-Foreign Goods	1.5	θ_c	1.5
Price Mark-up	10%	μ_p	1.1
Wage Mark-up	10%	μ_w	1.1
Resource Cost Share	50%	$\mathfrak{r}$	0.5
	National Accounts Ratios		
Labor Income Share	59.4%	α	0.3446
Investment/GDP	17.3%	Δ	0.0139
Government Spending/GDP	19.0%	s_g	0.1900
Imports/GDP	14.0%	b^c	0.7802
Capital/GDP	240.0%	κ_H^h	3.5329
	Fiscal Accounts Ratios and Rates		
Government Financing/GDP	75.00%	$\overline{gd^{rat}}$	2.9813
Marginal Labor Tax Rate	25.08%	$\bar{\tau}_L$	0.2508
Marginal Capital Tax Rate	34.44%	$\bar{\tau}_k$	0.3444
Consumption Tax Rate	3.42%	$\bar{\tau}_c$	0.0342
Labor Income Taxes/GDP	11.22%	ϖ^h	0.3174
Capital Income Taxes/GDP	3.46%	ϖ^k	0.2492

Table 2. Calibration: Financial Sector Steady State

Description	**Calibration Target**	**Parameter Symbol**	**Parameter Value**
	Bank Capital Ratios		
MCAR Regulatory Rate	10.5%	Θ	0.105
Endogenous Capital Buffer	5.0%	δ^b	0.0221
	Failure Rates		
MCAR Violation Rate	2.5% p.q.	σ^b	0.0252
Bankruptcy Rate, Domestic Loans	1.5% p.q.	ξ_H^h	0.1245
Bankruptcy Rate, Foreign Loans	1.5% p.q.	ξ_H^f	0.0943
	Real Interest Rates		
Policy/Wholesale Rate	3.00%	β_{fi}	0.9975
Government Bond Rate	2.80%	γ	1.5365
Interbank Lending Rate	3.25%	ζ	0.2794
Interbank Deposit Rate	3.00%	μ_{dH}^b	1.0000
Wholesale Rate, Domestic Loans	3.46%	χ	0.0028
Wholesale Rate, Foreign Loans	3.56%	κ_H^f	0.2783
Retail Rate, Domestic Loans	5.35%	σ_H^h	0.7655
Retail Rate, Foreign Loans	5.10%	σ_H^f	0.6040
Retail Rate, Domestic Deposits	1.50%	μ_{dH}^h	0.9963
Retail Rate, Foreign Deposits	1.50%	μ_{dH}^f	0.9963
	Borrower Balance Sheets		
Retail Loans to Domestic HH/GDP	120%	β_{hh}	0.9901
Retail Loans to Foreign HH/GDP	15%	φ_b	0.6656
Retail Deposits of Foreign/GDP	15%	b^o	0.8003
Retail Deposits for Consumption/GDP	53%	$\varkappa^{ci}$	1.6990
Retail Deposits for Production/GDP	12%	$\varkappa^y$	8.2181
Interbank Deposits (=Loans by FXMR)	20%	ϑ_b	0.8500
	Interest Elasticities		
FI Interest Semi-Elasticity Bonds ϵ_b^{fi}	250	ϑ_{fi}	2.0000
Elasticity of Interest Rate w.r.t. Debt	2 bp per pp	ϕ_f	0.00005
	Substitutability of Monies		
EoS Home-Foreign Currencies	1.5	θ_o	1.5
EoS Deposits-CBDC Transition	5.0	θ_d	5.0
EoS Deposits-CBDC Post-CBDC	2.0	θ_d	2.0

Table 3. Calibration: CBDC Steady State

a. Transition Simulation

Description	**Calibration Target**	**Parameter Name**	**Parameter Value**
Home CBDC/GDP	30%	$\overline{m^{rat}}$	30
Foreign CBDC/GDP	0%	$\overline{m^{rat}}^*$	0
Home Government Debt/GDP	45%	$\overline{gd^{rat}}$	2.9813
Foreign Government Debt/GDP	75%	$\overline{gd^{rat}}^*$	2.9813
Endogenous Capital Buffer Home	5%	δ^b	0.0134
Endogenous Capital Buffer Foreign	5%	δ^{b^*}	0.0212
Home Spread Deposits-CBDC	0.50%	$\eth$	1.053
Foreign Spread Deposits-CBDC	-	-	-
Monetary Policy Inertia	0	i_i	0
Monetary Policy Inflation Gap	1.5	i_π	1.5
Monetary Policy Output Growth	0.2	i_y	0.2
CBDC Policy Credit Gap	-	-	-
CBDC Policy Inflation Gap	-	-	-
Fiscal Policy Output Gap	0.5	$dgdp$	0.5

b. Business Cycle Simulations

Description	**Calibration Target**	**Parameter Name**	**Parameter Value**
Home CBDC/GDP	30%	$\overline{m^{rat}}$	30
Foreign CBDC/GDP	30%	$\overline{m^{rat}}^*$	30
Home Government Debt/GDP	45%	$\overline{gd^{rat}}$	2.9813
Foreign Government Debt/GDP	45%	$\overline{gd^{rat}}^*$	2.9813
Endogenous Capital Buffer Home	5%	δ^b	0.0126
Endogenous Capital Buffer Foreign	5%	δ^{b^*}	0.0126
Home Spread Deposits-CBDC	0.50%	$\eth$	0.8360
Foreign Spread Deposits-CBDC	0.50%	$\eth^*$	0.8360
Dom. Ccy. Consumption Deposits/GDP	24.46%	$b^m_{H,ci}$ / $b^{m^*}_{F,ci}$	0.4661
Dom. Ccy. Production Deposits/GDP	5.48%	$b^m_{H,y}$ / $b^{m^*}_{F,y}$	0.3483
For. Ccy. Consumption Deposits/GDP	6.92%	$b^m_{F,ci}$ / $b^{m^*}_{H,ci}$	0.5339
Monetary Policy Inertia	-	i_i	benchmark, or estimated, or optimized
Monetary Policy Inflation Feedback	-	i_π	
Monetary Policy Output Feedback	-	i_y	
CBDC Policy Credit Feedback	-	m_{cred}	
CBDC Policy Inflation Feedback	-	m_π	
Fiscal Policy Output Feedback	0	$dgdp$	0

Table 4. Estimation: Data Sources

Variable	Transformation	Source
Real GDP (growth per capita)	QoQ Annualized	BEA
Real Consumption (growth per capita)	QoQ Annualized	BEA
Real Gov. Spending (growth per capita)	QoQ Annualized	BEA
Real Gross Capital Formation (growth per capita)	QoQ Annualized	OECD
Hours Worked (total)	Level	BLS
Real Hourly PCE-Deflated Wages (growth)	QoQ Annualized	BLS
Inflation Rate of PCE Price Level	QoQ Annualized	BEA
Wu-Xia Shadow Fed Funds Rate	Detrended	FRB Atlanta
Total Domestic Credit (growth per capita)	QoQ Annualized	Federal Reserve
BAA Corporate Spread	Level	Moody's
Depreciation Rate of Broad Dollar Index	QoQ Annualized	BIS
Working Age Population (for per capita transformations)	Level	OECD

Table 5. Estimation: Parameter Estimates

a. Structural Parameters

Description		**Posterior**		**Prior**		
		Mean	90% CI	Distribution	Mean	Std
MP inertia	$\imath_i$	0.7456	[0.7236 ; 0.7710]	Beta	0.5	0.2
MP response to π	i_π	1.2829	[1.2598 ; 1.3191]	Normal	1.5	0.2
MP response to y	i_y	0.0134	[0.0000 ; 0.0350]	Normal	0.2	0.1
Price stickiness	ϕ_p	372.30	[364.29 ; 381.90]	Normal	200	50
Habit persistence	ν	0.6299	[0.6141 ; 0.6508]	Beta	0.5	0.1
Investment adj. costs	ϕ_i	0.7844	[0.7700 ; 0.8001]	Normal	0.5	0.1
Loan adj. costs x 10^3	ϕ_l x 10^3	0.3513	[0.3301 ; 0.3803]	Normal	0.5	0.1

b. Shock Autocorrelation

Description		**Posterior**		**Prior**		
		Mean	90 % CI	Dist.	Mean	Std
Credit Supply	ρ_{cred}	0.9896	[0.9808 ; 0.9981]	Beta	0.5	0.2
Bank Leverage	ρ_{lev}	0.6381	[0.6073 ; 0.6753]	Beta	0.5	0.2
Money Demand	ρ_{mon}	0.9468	[0.9273 ; 0.9657]	Beta	0.5	0.2
Currency Demand	ρ^*_{ccy}	0.9782	[0.9614 ; 0.9948]	Beta	0.5	0.2
Consumption Demand	ρ_c	0.9842	[0.9767 ; 0.9906]	Beta	0.5	0.2
Investment Demand	ρ_i	0.8713	[0.8468 ; 0.8991]	Beta	0.5	0.2
Government Demand	ρ_g	0.9422	[0.9269 ; 0.9578]	Beta	0.5	0.2
	ρ_{eg}	0.3003	[0.2573 ; 0.3386]	Beta	0.5	0.2
Inventory Demand	ρ_v	0.9422	[0.9246 ; 0.9529]	Beta	0.5	0.1
Import Demand	ρ_m	0.8810	[0.8556 ; 0.9053]	Beta	0.5	0.1
Technology	ρ_a	0.9791	[0.9618 ; 0.9960]	Beta	0.5	0.2

c. Shock Standard Errors

Description		**Posterior**		**Prior**		
		Mean	90 % CI	Dist.	Mean	Std
Credit Supply	$\sigma_{\epsilon_{cred}}$	0.0492	[0.0412 ; 0.0568]	Inv.Gamma	0.1	10
Bank Leverage	$\sigma_{\epsilon_{lev}}$	0.1806	[0.1573 ; 0.2040]	Inv.Gamma	0.1	10
Money Demand	$\sigma_{\epsilon_{mon}}$	0.0184	[0.0162 ; 0.0206]	Inv.Gamma	0.1	10
Currency Demand	$\sigma_{\epsilon^*_{ccy}}$	0.1001	[0.0794 ; 0.1193]	Inv.Gamma	0.1	10
Consumption Demand	σ_{ϵ_c}	0.0172	[0.0149 ; 0.0195]	Inv.Gamma	0.01	1
Investment Demand	σ_{ϵ_i}	0.0066	[0.0058 ; 0.0074]	Inv.Gamma	0.01	1
Government Demand	σ_{ϵ_g}	0.0069	[0.0061 ; 0.0076]	Inv.Gamma	0.01	1
Inventory Demand	σ_{ϵ_v}	0.0037	[0.0032 ; 0.0043]	Inv.Gamma	0.01	1
Import Demand	σ_{ϵ_m}	0.0045	[0.0028 ; 0.0060]	Inv.Gamma	0.01	1
Technology	σ_{ϵ_a}	0.0075	[0.0067 ; 0.0083]	Inv.Gamma	0.01	1
Price Markup	$\sigma_{\epsilon_{mup}}$	0.0041	[0.0012 ; 0.0076]	Inv.Gamma	0.005	0.5
Price Meas. Error	$\sigma_{\epsilon_{mep}}$	0.0043	[0.0037 ; 0.0048]	Inv.Gamma	0.005	0.5
Wage Markup	$\sigma_{\epsilon_{muw}}$	0.0026	[0.0013 ; 0.0039]	Inv.Gamma	0.005	0.5
Wage Meas. Error	$\sigma_{\epsilon_{ew}}$	0.0079	[0.0057 ; 0.0102]	Inv.Gamma	0.005	0.5
Monetary Policy	$\sigma_{\epsilon_{int}}$	0.0010	[0.0009 ; 0.0011]	Inv.Gamma	0.001	0.1

Table 6. Estimation: Variance Decomposition

Share of variance accounted for by ...	**Financial Shocks**	**Demand Shocks**	**Supply Shocks***
$400\left(\Delta\log\left(y_t/y_{t-1}\right)\right)$	44	50	6
$400\left(\Delta\log\left(c_t/c_{t-1}\right)\right)$	61	32	7
$400\left(\Delta\log\left(I_t/I_{t-1}\right)\right)$	54	43	3
$400\left(\Delta\log\left(g_t/g_{t-1}\right)\right)$	0	100	0
$100\left(\log\left(h_t/\bar{h}\right)\right)$	12	85	3
$400\left(\Delta\log\left(w_t^{pr}/w_{t-1}^{pr}\right)\right)$	48	36	16
$400\left(\log\left(\pi_t^{pce}/\bar{\pi}^{pce}\right)\right)$	63	6	31
$400\left(\log\left(i_t/i_{t,trend}\right)\right)$	94	6	0
$400\left(\log\left(sp_t/\overline{sp}\right)\right)$	94	5	1
$400\left(\Delta\log\left(\ell_{H,t}^h/\ell_{H,t-1}^h\right)\right)$	93	6	1
$400\left(\log\left(\varepsilon_t\right)\right)$	95	5	0
* = including measurement error			

Table 7. Optimized Simple Rules - Maximized Welfare Gains

Row #	**Figure #**	**CBDC Rule**	**Fiscal Rule**	**CBDC Shocks**	**CBDC resp. to** ℓ_H^h/π^p	**CBDC Coeff. Value** $m_{cred/\pi}$	**π-Gap Coeff. Value** i_π	**y-Gap Coeff. Value** i_y	**Welfare Gain CCV** $\boldsymbol{\eta}$
1	-	-	BB	-	-	-	1.50	0.20	-2.01
2	5a	-	BB	-	-	-	3.00	0.65	-1.50
3	-	*INT*	*BB*	*No*	ℓ_H^h	*0.00*	*1.50*	*0.00*	*0.00*
4	5b	INT	BB	No	ℓ_H^h	1.00	3.00	0.08	+1.01
5	5b	INT	BB	No	ℓ_H^h	0.00	3.00	0.08	+0.57
6	5b	INT	BB	No	ℓ_H^h	0.50	3.00	0.08	+0.77
7	-	INT	BB	Yes	ℓ_H^h	1.00	3.00	0.12	+1.04
8	5c	Q	BB	No	ℓ_H^h	0.67	3.00	0.11	+0.63
9	5d	INT	BB	No	π^p	0.00	3.00	0.40	+0.57
10	5e	RES	BB	No	ℓ_H^h/π^p	0.18	3.00	0.37	+0.69
11	5f	CASH	BB	No	-	-	3.00	0.35	+0.65
12	5g, 5h	INT	AS	No	ℓ_H^h	1.00	3.00	0.13	+1.58

In all cases, $i_\pi \leq 3.0$ is imposed. Subject to this, $i_\pi = 3.0$ (and $i_i = 0$) is always optimal.
INT = interest rate rule, Q = quantity rule, RES = CBDC=Reserves, CASH = cash-like CBDC
BB = balanced budget rule, AS = automatic stabilizers with dgdp=0.34

Table 8. Optimized Simple Rules versus Fully Optimized Simple Rules

Deterministic Steady State	**OSR**	**FOSR**	**Difference FOSR-OSR**
$\bar{b}^{rat}$	45.0%	35.6%	-9.4%
$\bar{m}^{rat}$	30.0%	39.4%	+9.4%
$\bar{\imath}$	4.4%	4.2%	-0.2%
$\bar{\imath}_m$	2.4%	3.3%	+0.9%
$\overline{gdp}$			+1.0%
CCV			+0.16%
Stochastic Steady State	**OSR**	**FOSR**	**Difference FOSR-OSR**
$\tilde{b}^{rat}$	29.9%	14.8%	-15.1%
$\tilde{m}^{rat}$	46.8%	64.7%	+17.9%
$\tilde{\imath}$	4.0%	3.3%	-0.7%
$\tilde{\imath}_m$	2.8%	2.5%	-0.3%
$\widetilde{gdp}$			+1.8%
CCV			+0.13%
OSR: $\mathfrak{sp} = 1.005000$			
FOSR: $\mathfrak{sp} = 1.002375$			

Figure 1. Domestic and Cross-Border Gross Financial Flows

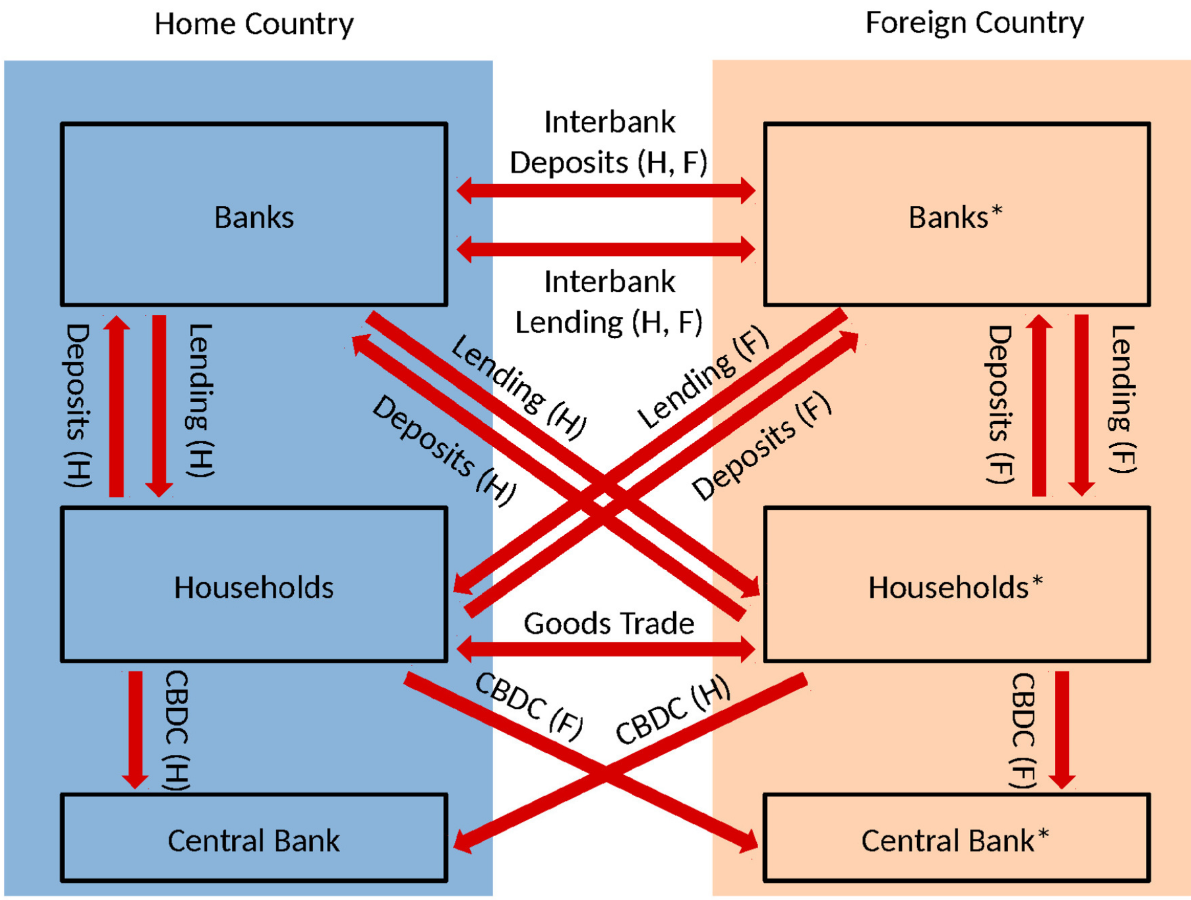
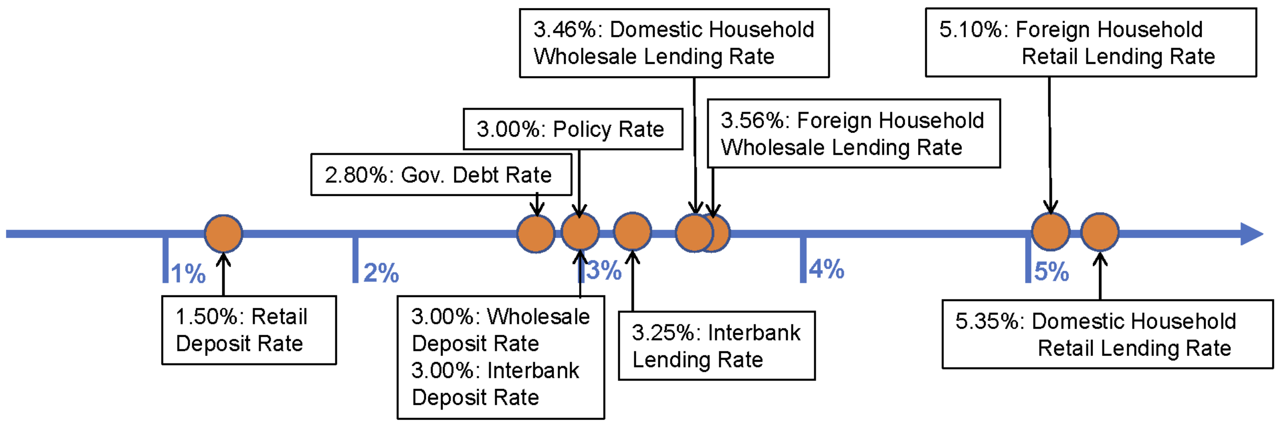


Figure 2. Calibration: Key Financial Variable Steady States

a. Real Interest Rates



(in % p.a.)

b. Bank Balance Sheets

Home Banks

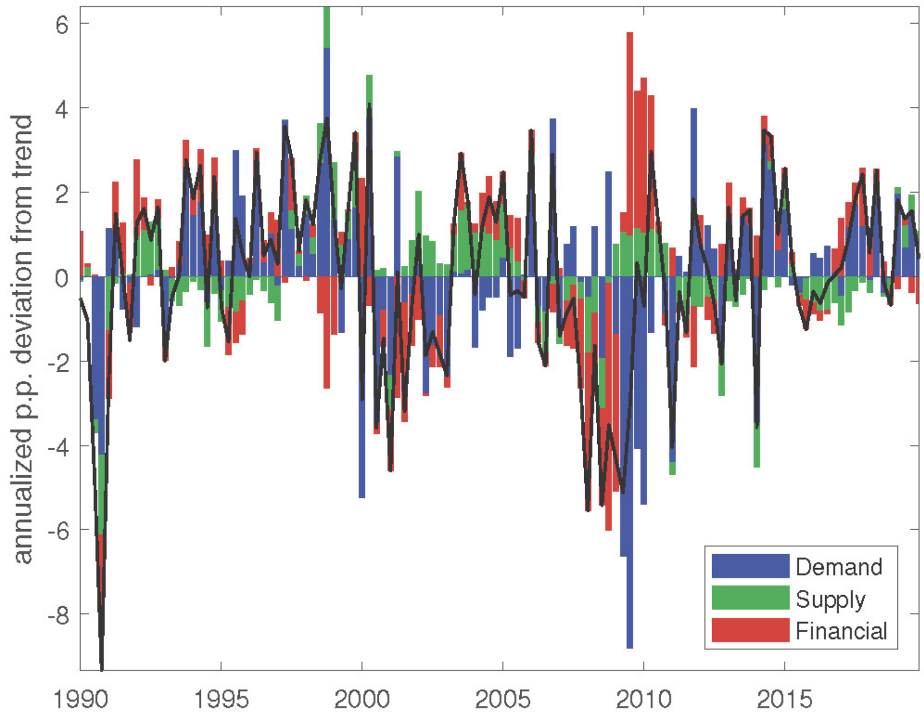
Home HH Loans	120	Net Worth	23
		Home FI Deposits	32
		Home HH Deposits	65
Foreign HH Loans	15	Foreign HH Deposits	15
Home Ccy Nostro	20	Home Ccy Vostro	20
Foreign Cccy Nostro	20	Foreign Cccy Nostro	20

Foreign Banks

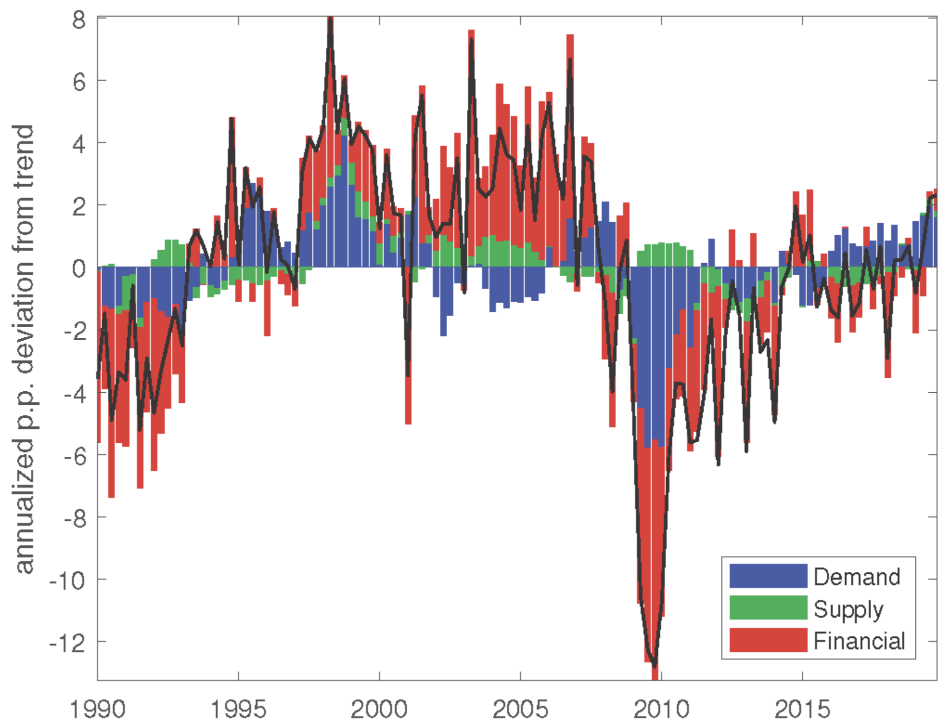
Foreign HH Loans	120	Net Worth	23
		Foreign FI Deposits	32
		Foreign HH Deposits	65
Home HH Loans	15	Home HH Deposits	15
Foreign Cccy Nostro	20	Foreign Cccy Nostro	20
Home Ccy Nostro	20	Home Ccy Vostro	20

(in % of GDP)

Figure 3. Estimation: Historical Decomposition



Real GDP Growth (deviations from trend)



Real Credit Growth (deviations from trend)

Figure 4. Transition Simulation

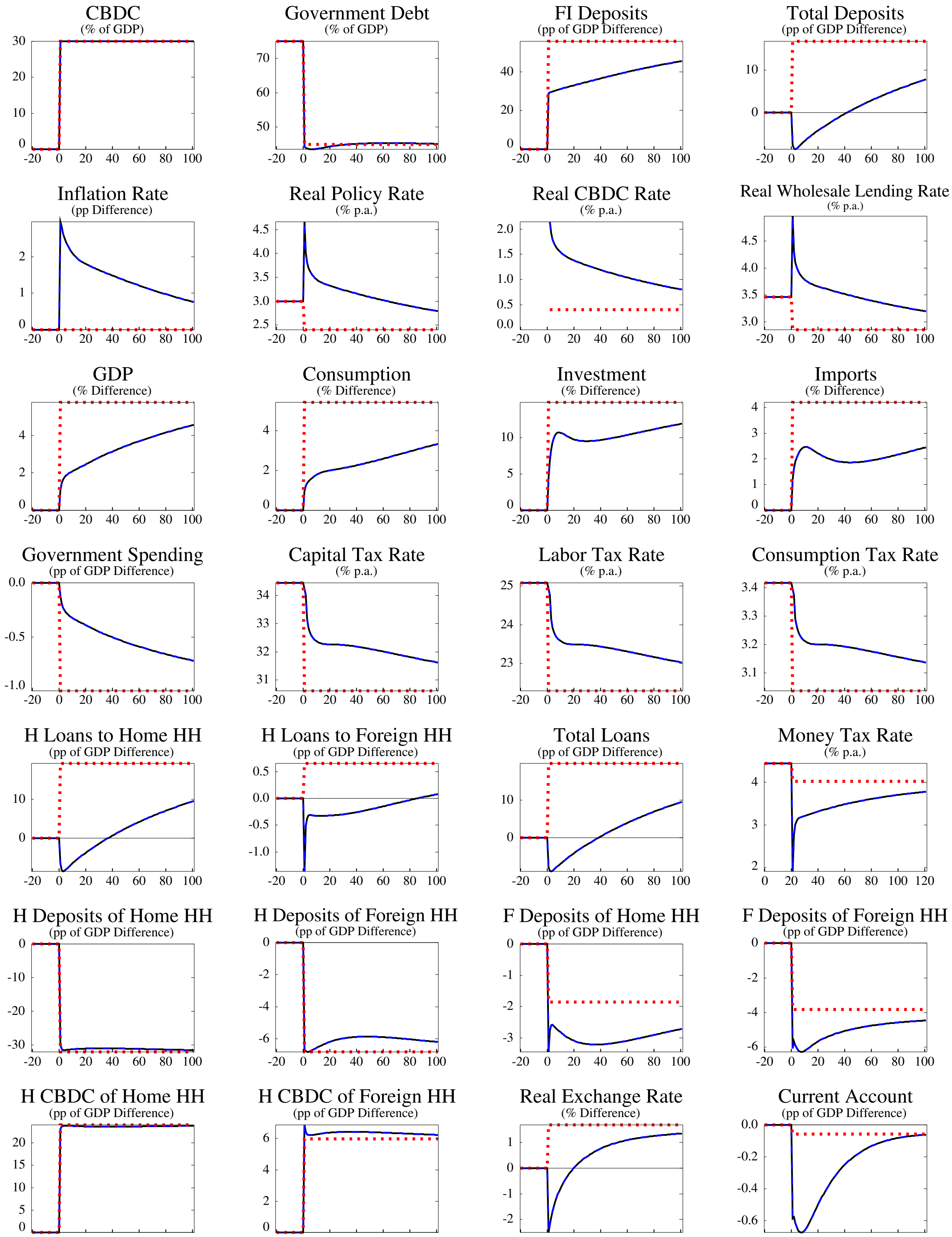
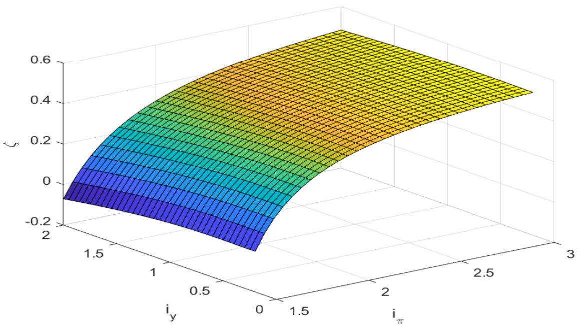
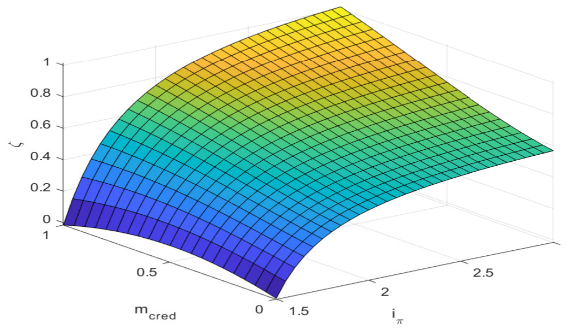


Figure 5. Optimized Simple Rules - Welfare Surfaces

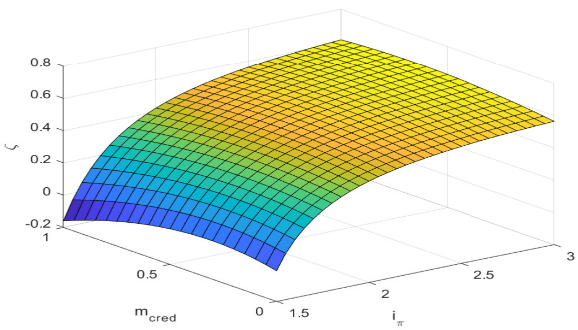
a. Pre-CBDC



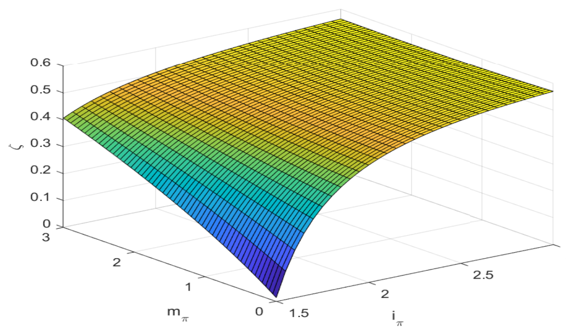
b. Interest Rate Rule with Credit Gap



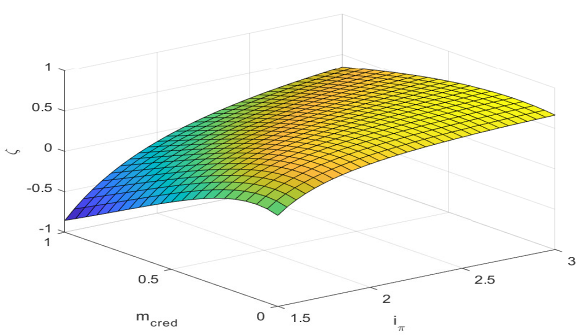
c. Quantity Rule with Credit Gap



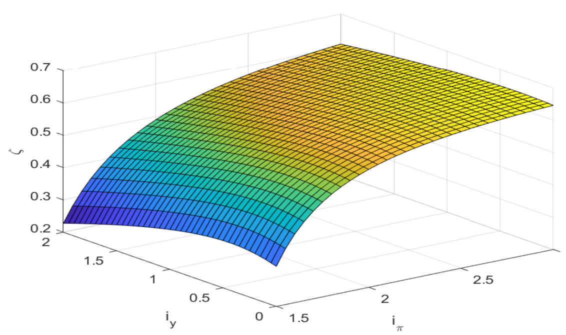
d. Interest Rate Rule with Inflation Gap



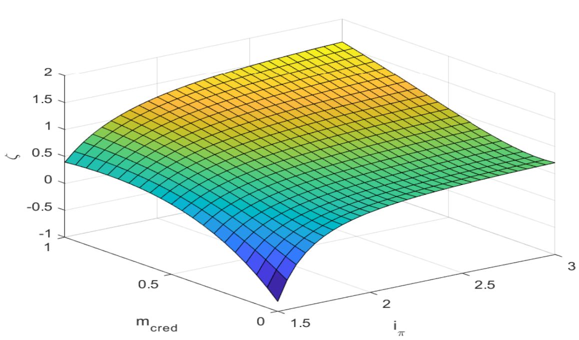
e. Reserves Rule



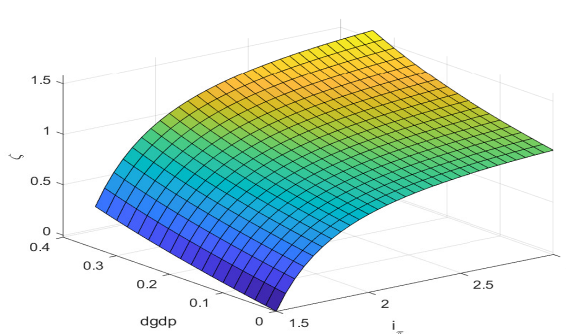
f. Cash-like CBDC



g. Interest Rate Rule with Credit Gap plus Automatic Stabilizers (i_π vs. m_{cred})



h. Interest Rate Rule with Credit Gap plus Automatic Stabilizers (i_π vs. $dgdp$)



(vertical axis: ζ = welfare gain relative to zero welfare baseline)

Figure 6. Counterfactual Simulation for Optimized Simple Rules - Time Series Decomposition

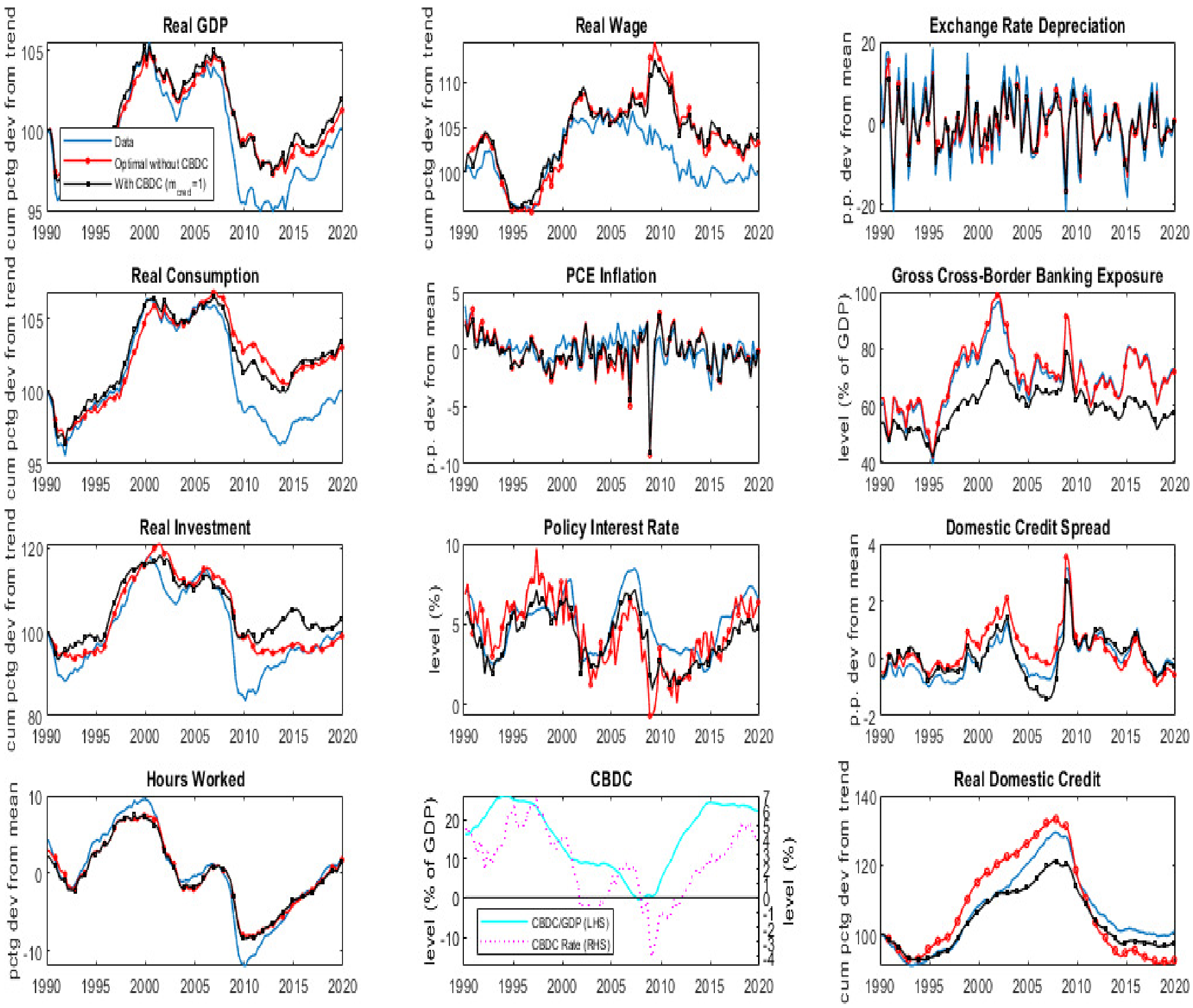
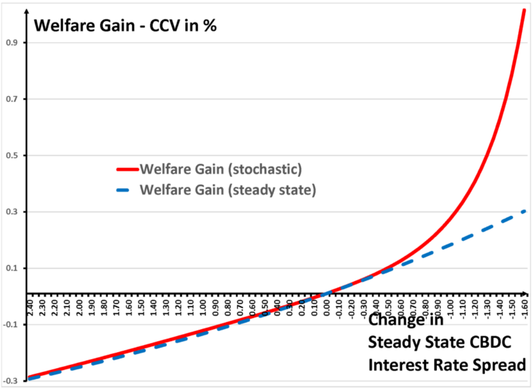
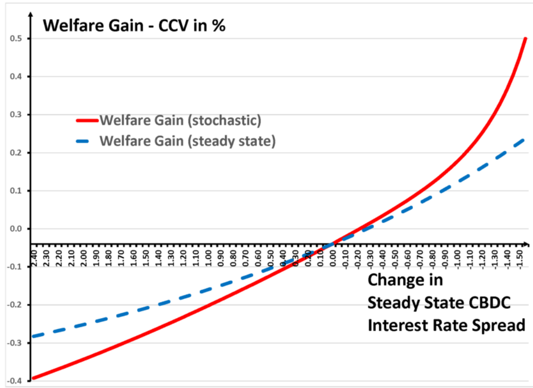


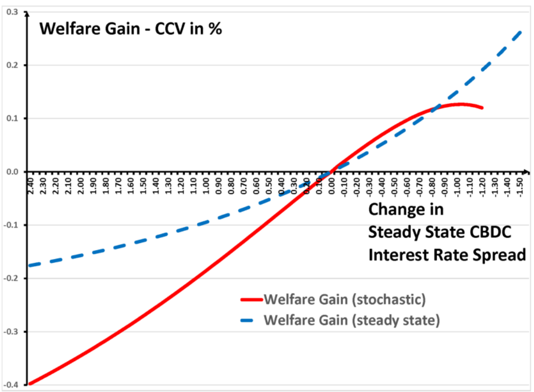
Figure 7. Fully Optimized Simple Rules - Steady State CBDC Rate and Welfare Gains



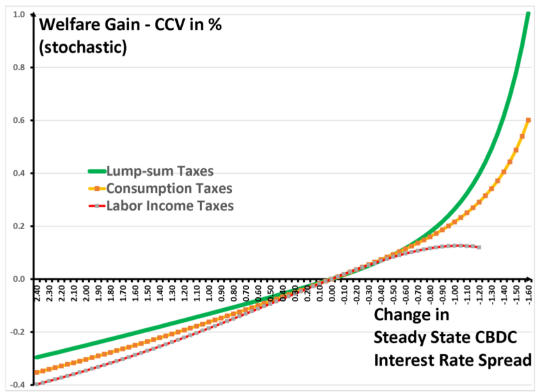
a. Lump-sum Taxes



b. Consumption Taxes

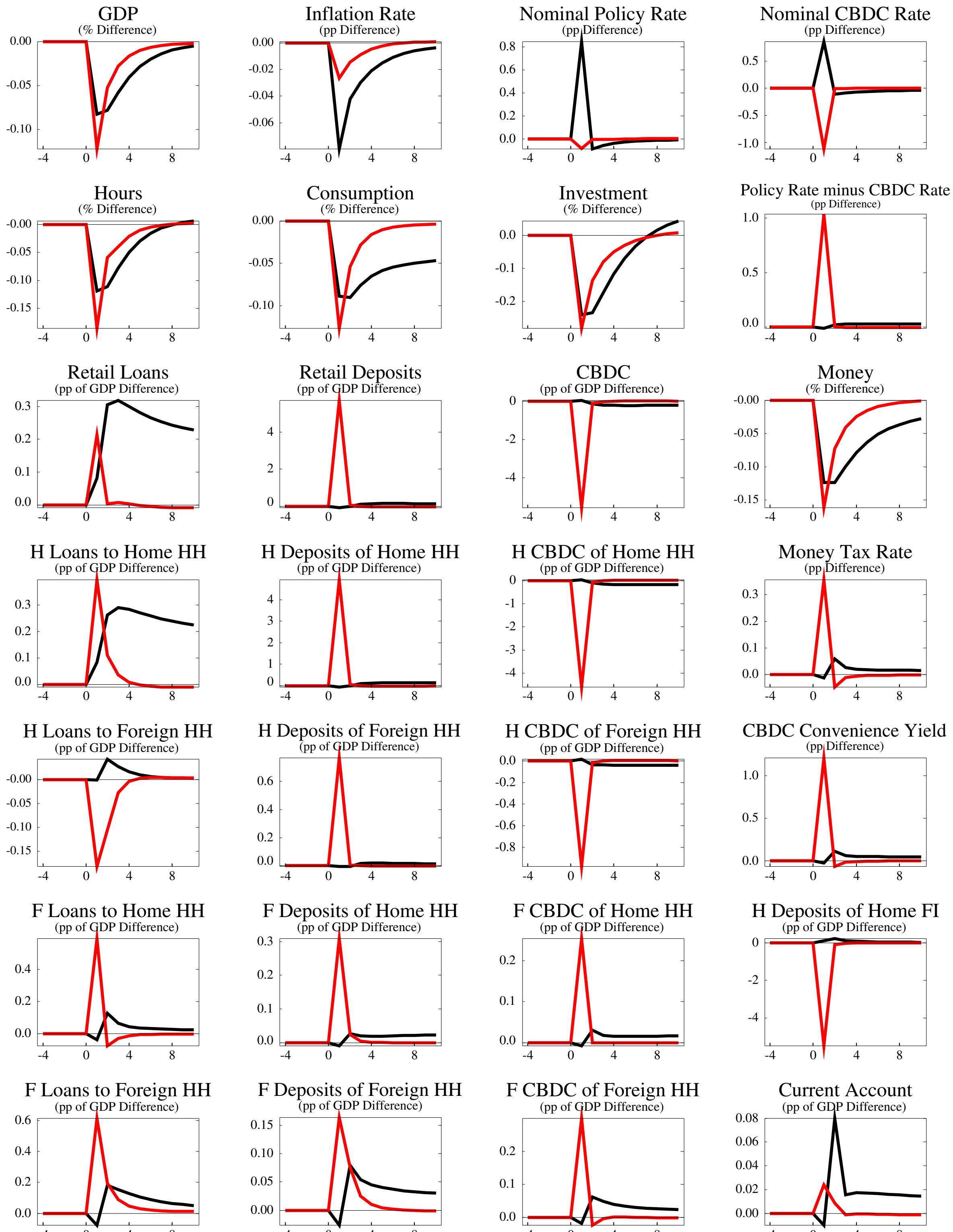


c. Labor Income Taxes



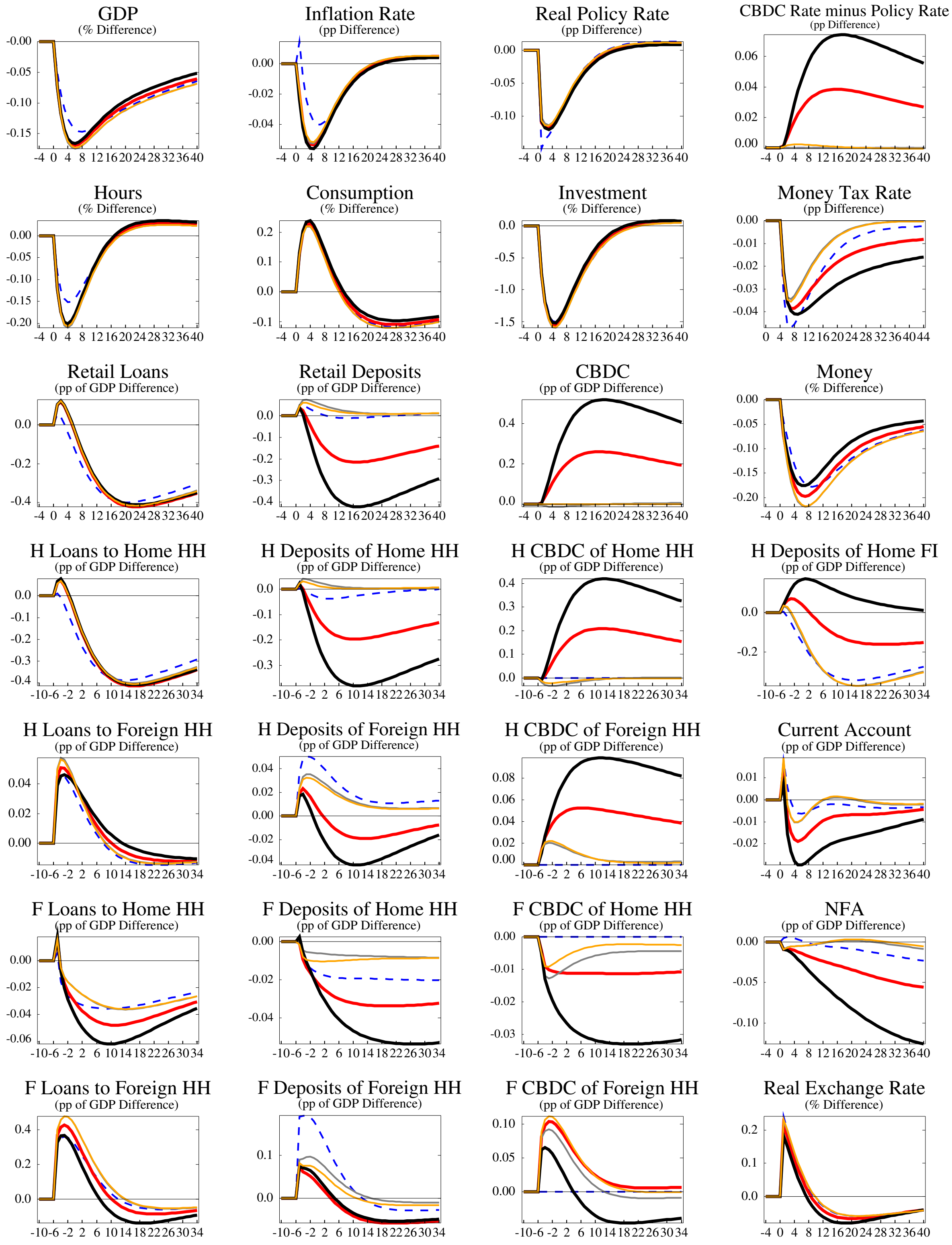
d. All Taxes (stochastic)

Figure 8. IRF - Monetary Policy Shocks



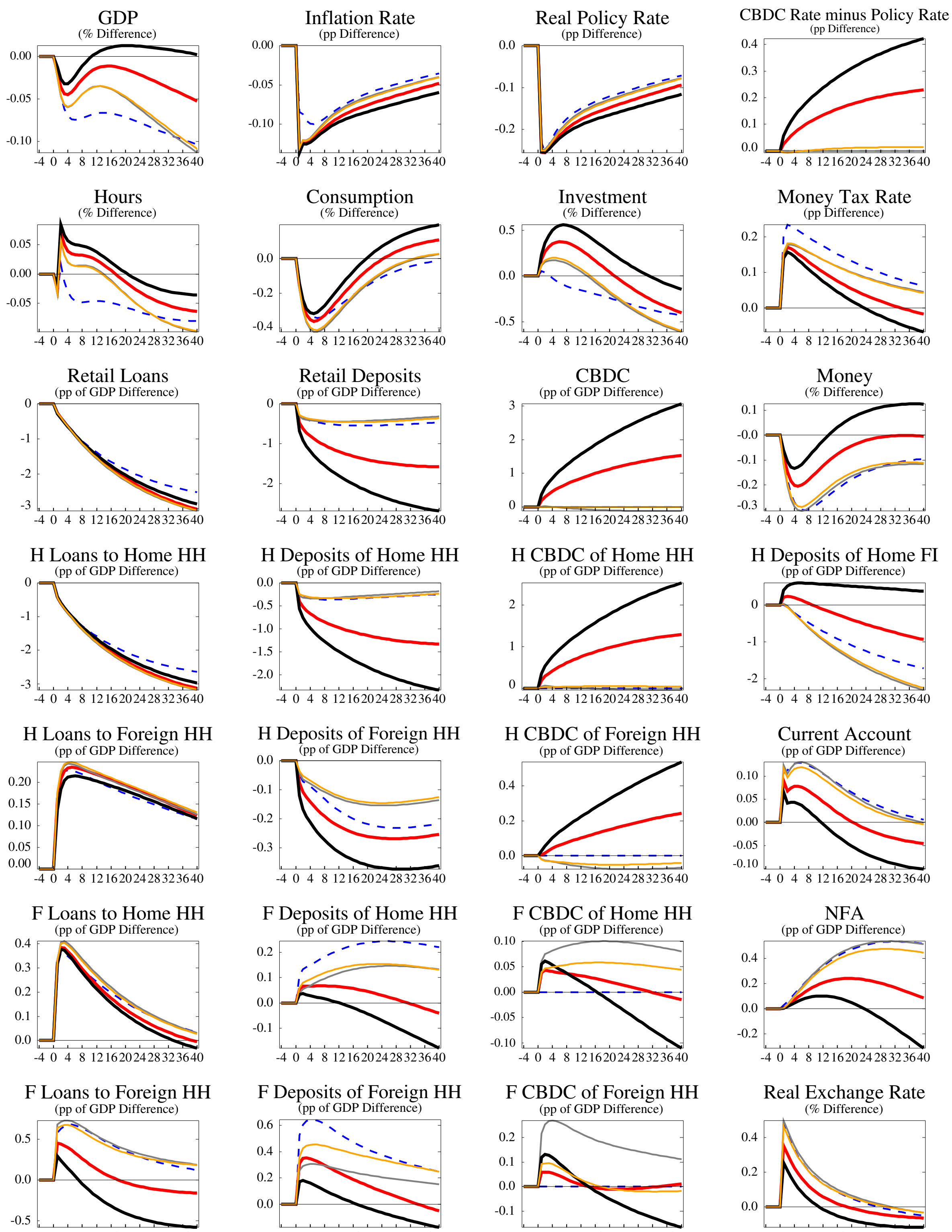
(black solid = Taylor rule shock,
red solid = CBDC rule shock)

Figure 9. IRF - Interest Rate vs. Quantity Rules - Home Investment Demand



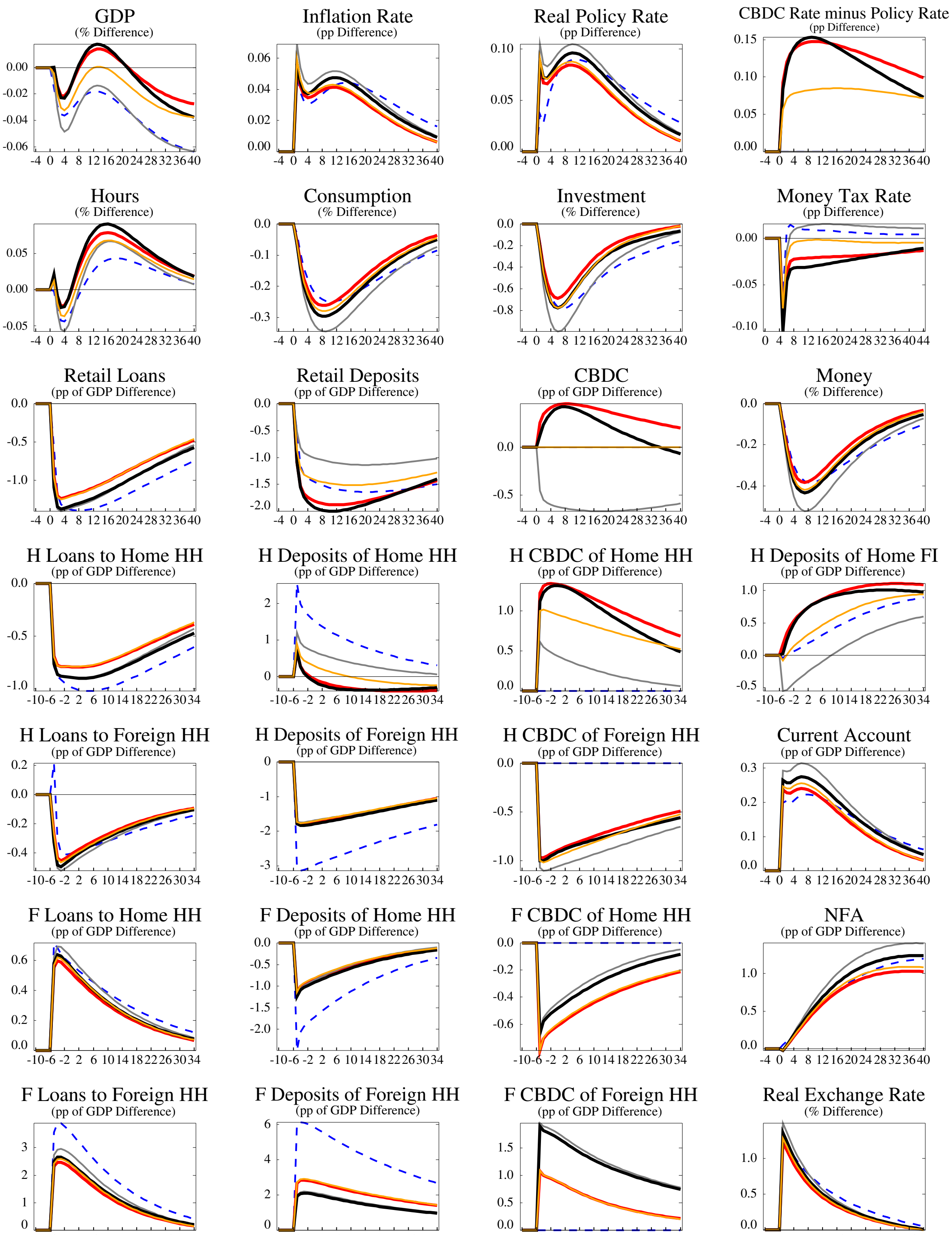
(blue dashed = pre-CBDC,
black = INT-rule with optimized credit feedback, grey = passive (fixed spread) INT-rule,
red = Q-rule with optimized credit feedback, orange = passive (fixed quantity) Q-rule)

Figure 10. IRF - Interest Rate vs. Quantity Rules - Home Credit Supply



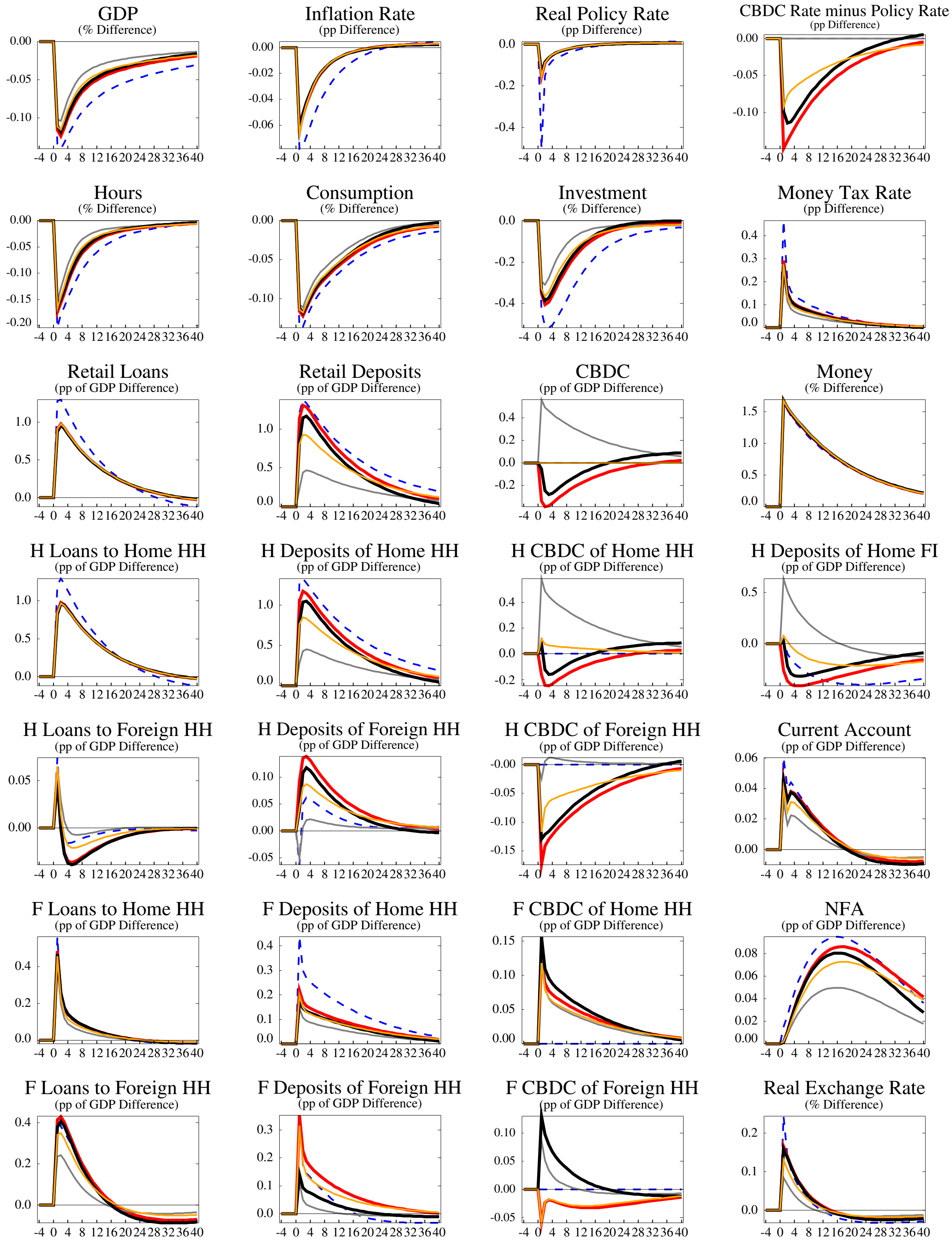
(blue dashed = pre-CBDC
black = INT-rule with optimized credit feedback, grey = passive (fixed spread) INT-rule
red = Q-rule with optimized credit feedback, orange = passive (fixed quantity) Q-rule)

Figure 11. IRF - Interest Rate vs. Quantity Rules - Foreign Currency Demand



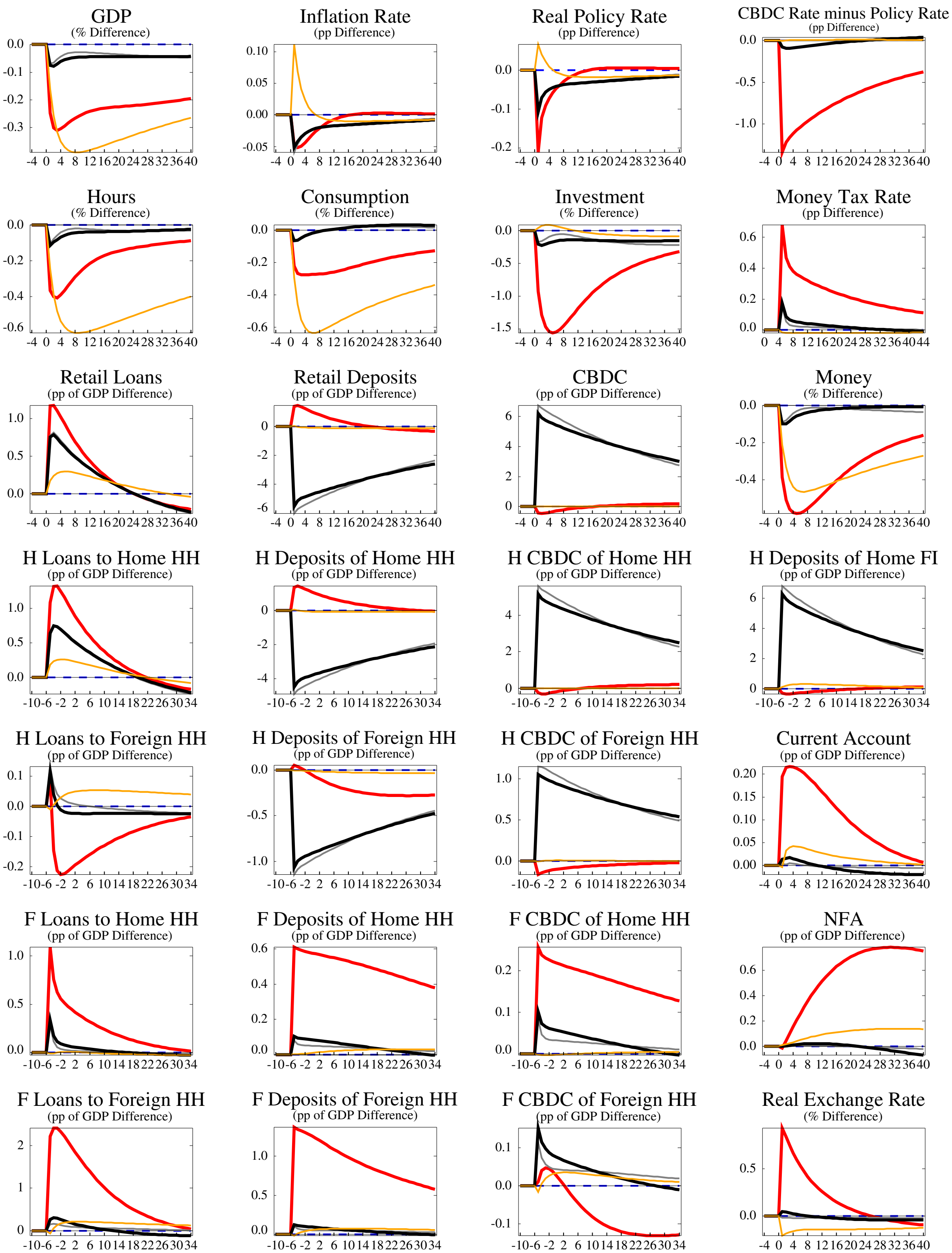
(blue dashed = pre-CBDC,
black = INT-rule with optimized credit feedback, grey = passive (fixed spread) INT-rule
red = Q-rule with optimized credit feedback, orange = passive (fixed quantity) Q-rule)

Figure 12. IRF - Interest Rate vs. Quantity Rules - Home Money Demand



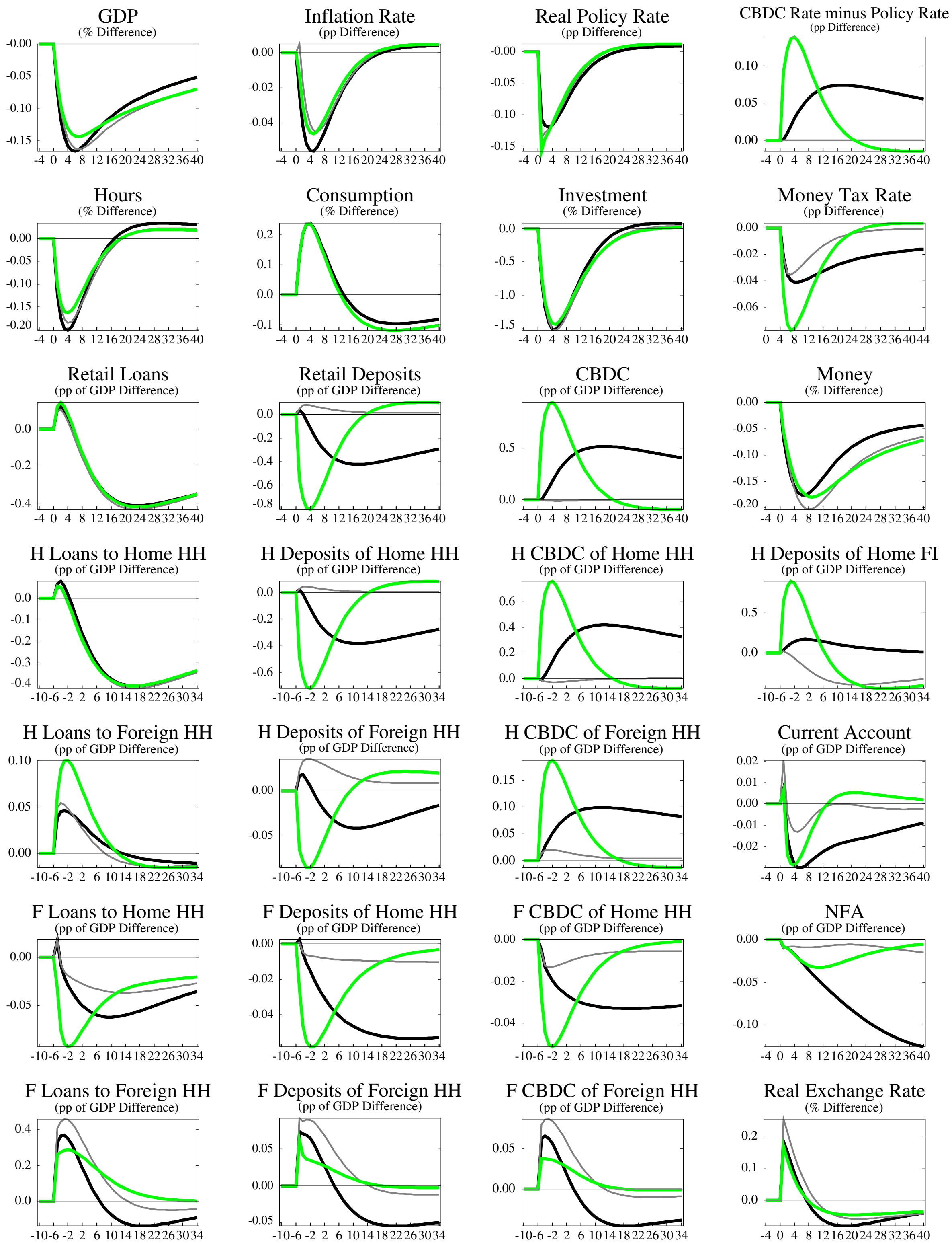
(blue dashed = pre-CBDC,
black = INT-rule with optimized credit feedback, grey = passive (fixed spread) INT-rule
red = Q-rule with optimized credit feedback, orange = passive (fixed quantity) Q-rule)

Figure 13. IRF - Interest Rate vs. Quantity Rules - Global Run into Home CBDC



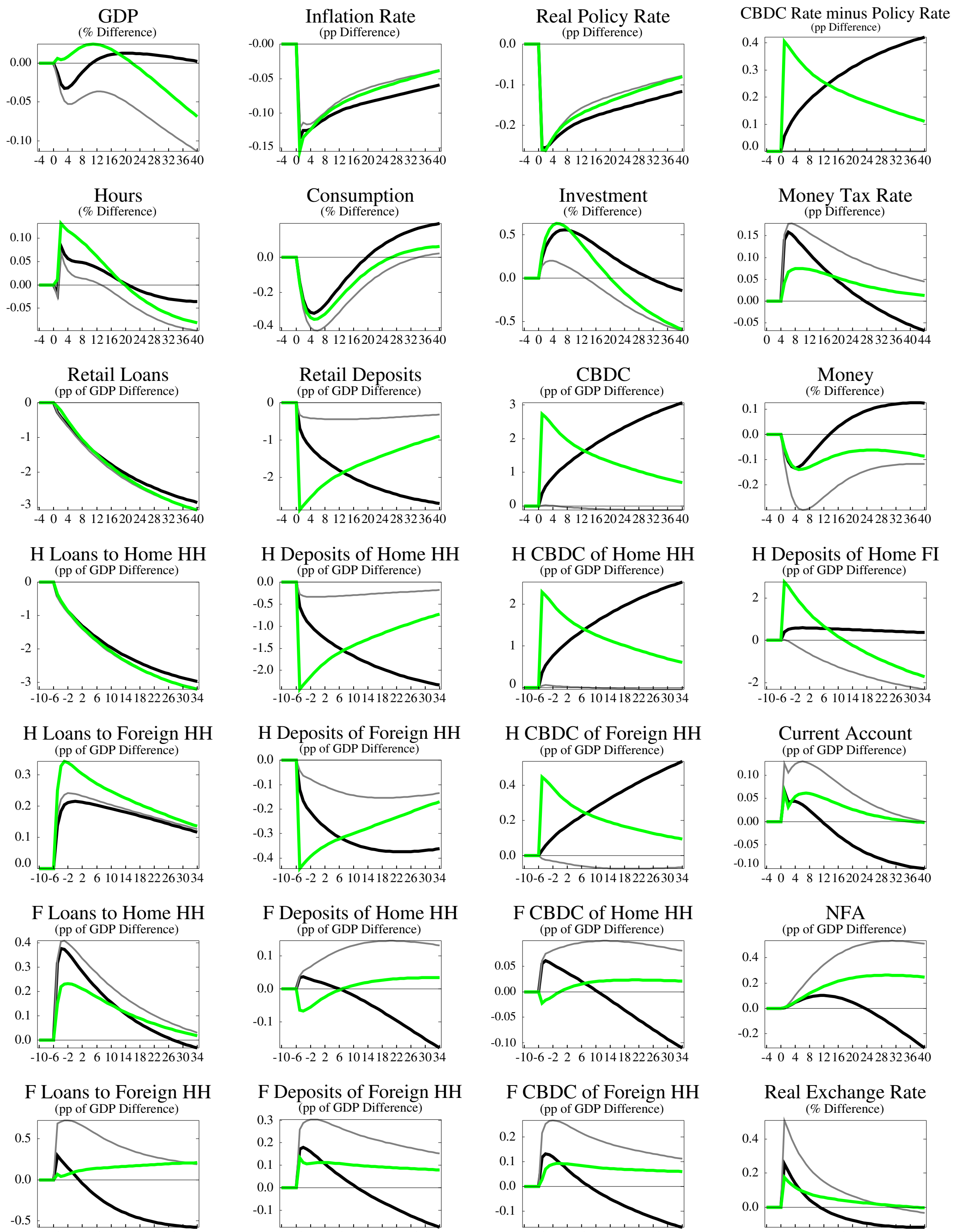
(blue dashed = pre-CBDC,
black = INT-rule with optimized credit feedback, grey = passive (fixed spread) INT-rule
red = Q-rule with optimized credit feedback, orange = passive (fixed quantity) Q-rule)

Figure 14. IRF - Credit vs. Inflation Feedback Rules - Home Investment Demand



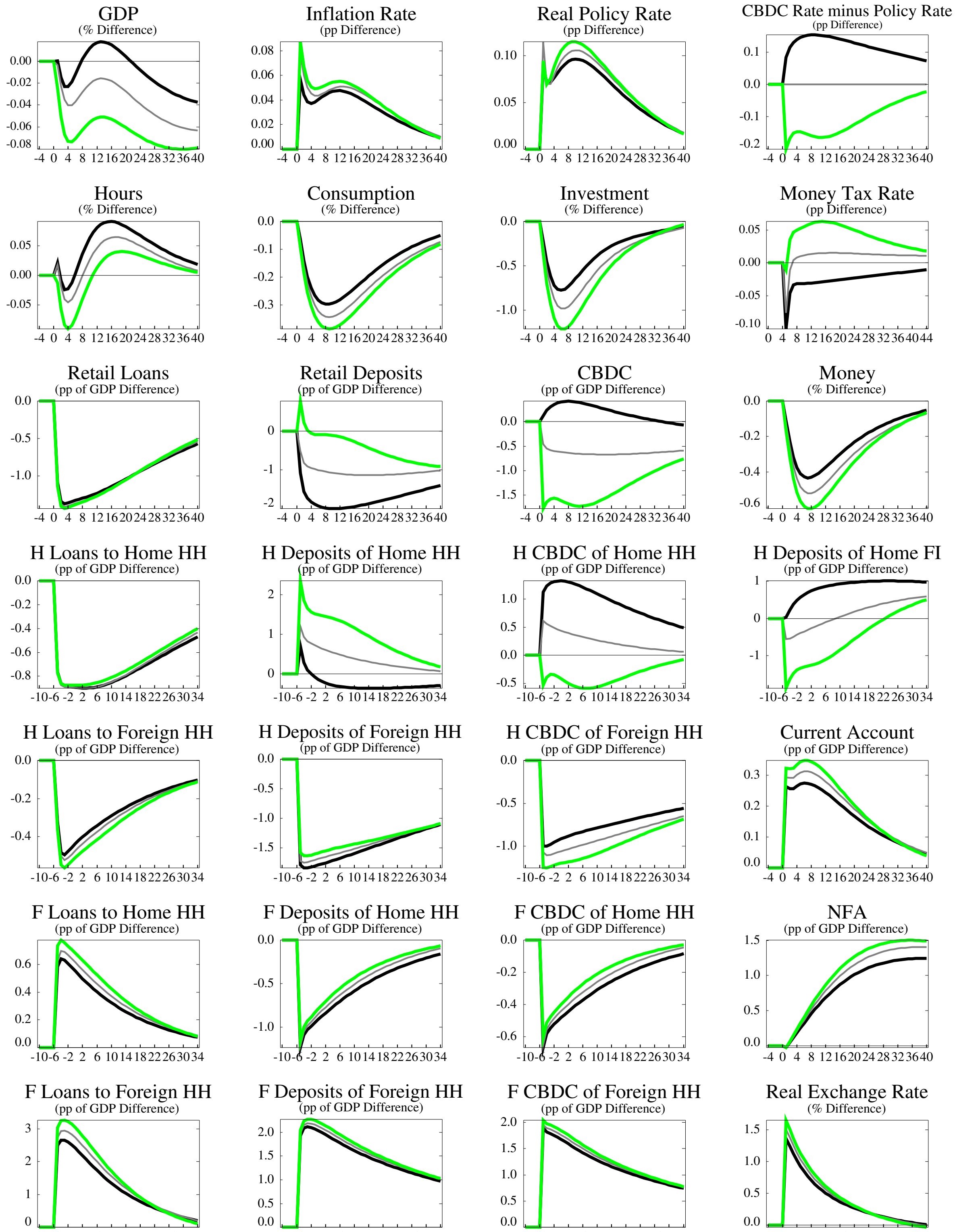
(black = INT-rule with optimized credit feedback,
grey = INT-rule with optimized inflation feedback,
green = INT-rule with aggressive inflation feedback)

Figure 15. IRF - Credit vs. Inflation Feedback Rules - Home Credit Supply



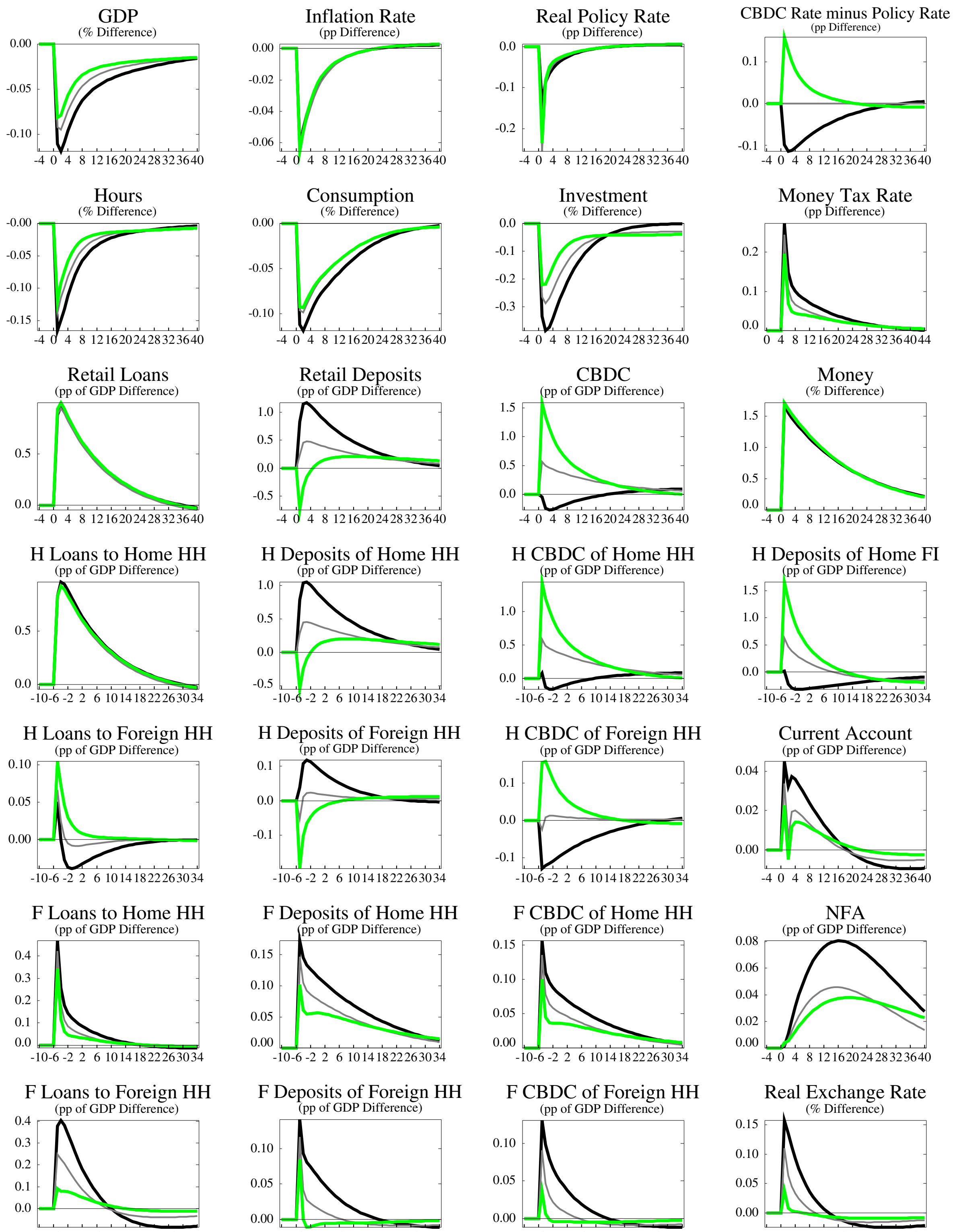
(black = INT-rule with optimized credit feedback,
grey = INT-rule with optimized inflation feedback,
green = INT-rule with aggressive inflation feedback)

Figure 16. IRF - Credit vs. Inflation Feedback Rules - Foreign Currency Demand



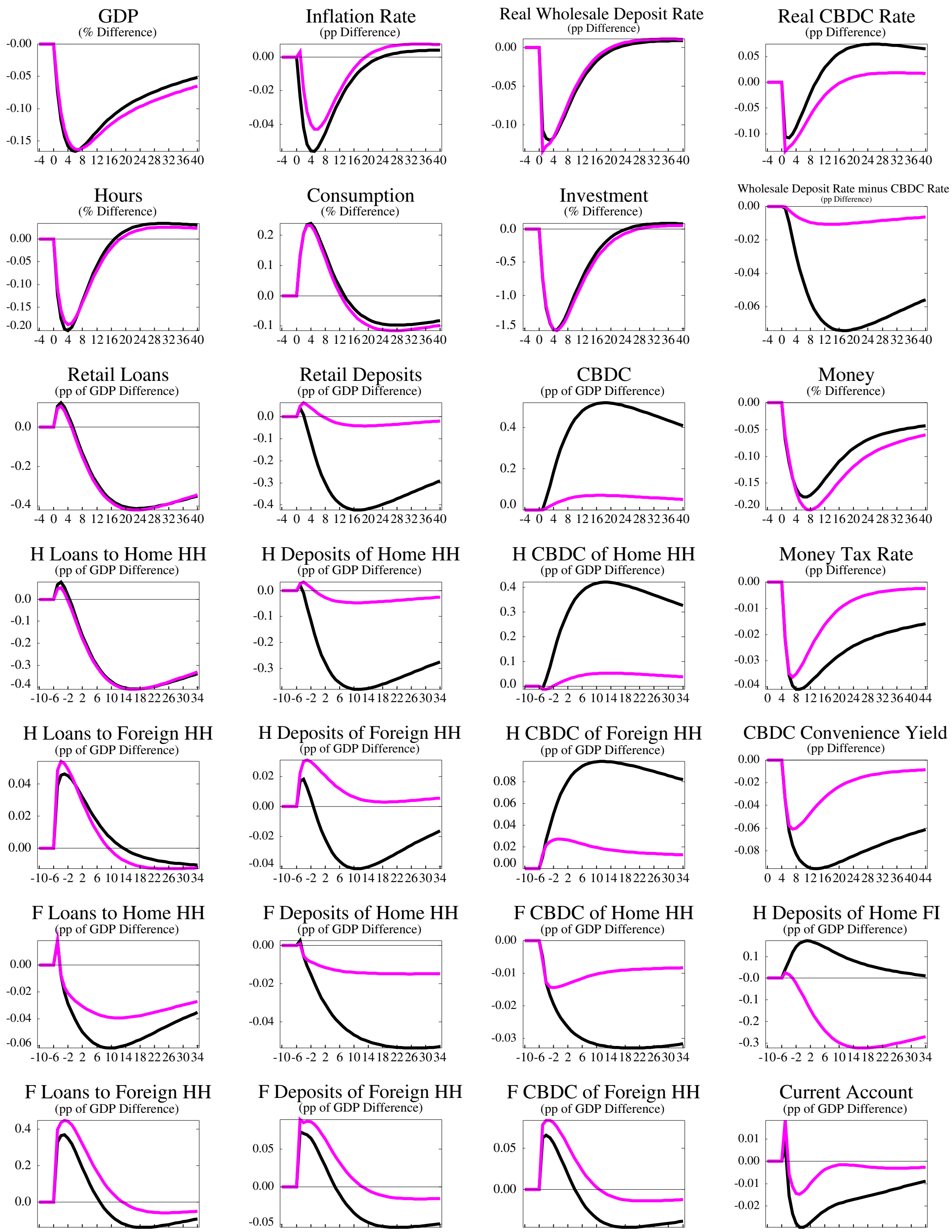
(black = INT-rule with optimized credit feedback,
grey = INT-rule with optimized inflation feedback,
green = INT-rule with aggressive inflation feedback)

Figure 17. IRF - Credit vs. Inflation Feedback Rules - Home Money Demand



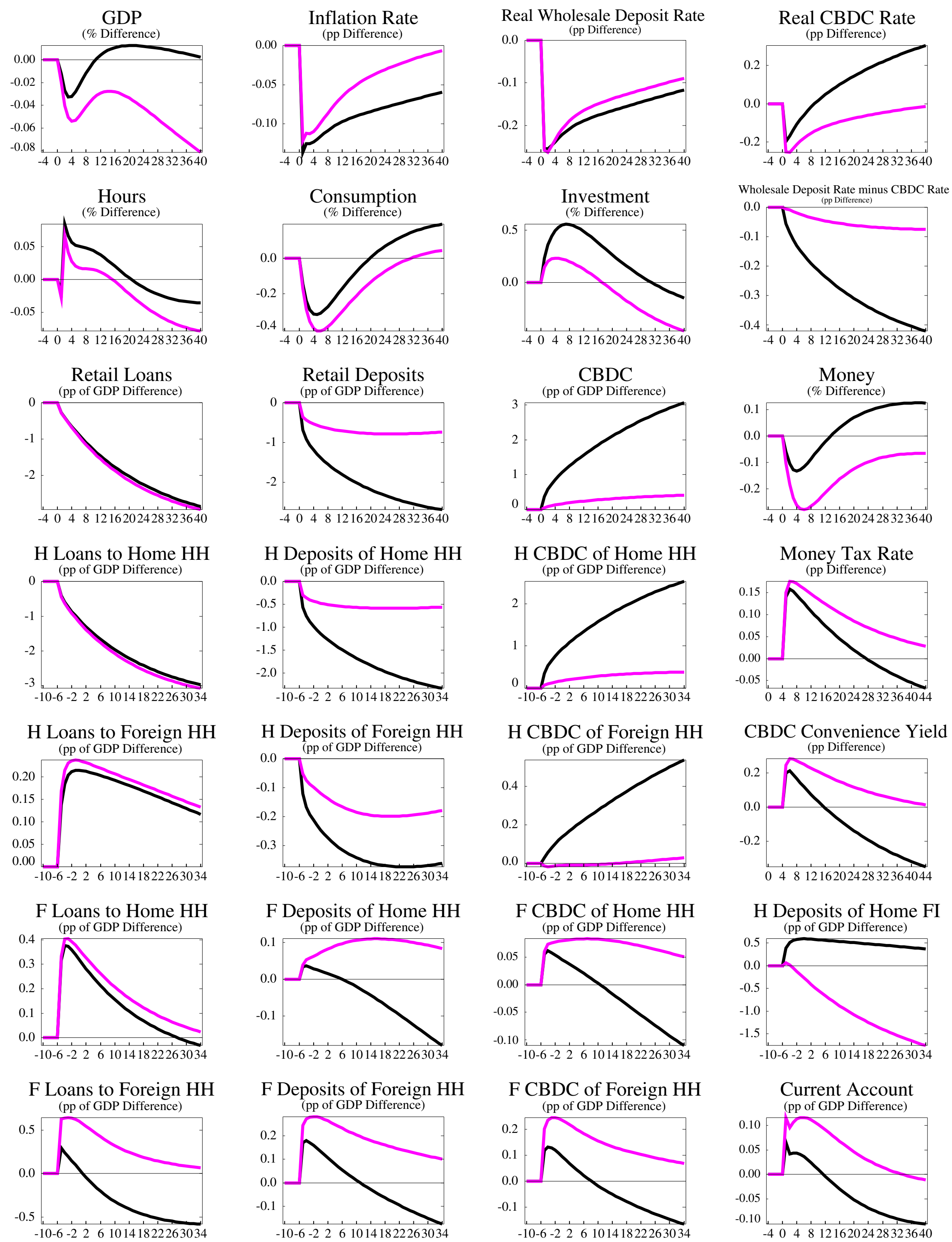
(black = INT-rule with optimized credit feedback,
grey = INT-rule with optimized inflation feedback,
green = INT-rule with aggressive inflation feedback)

Figure 18. IRF - Interest Rate vs. Reserves Rules - Home Investment Demand



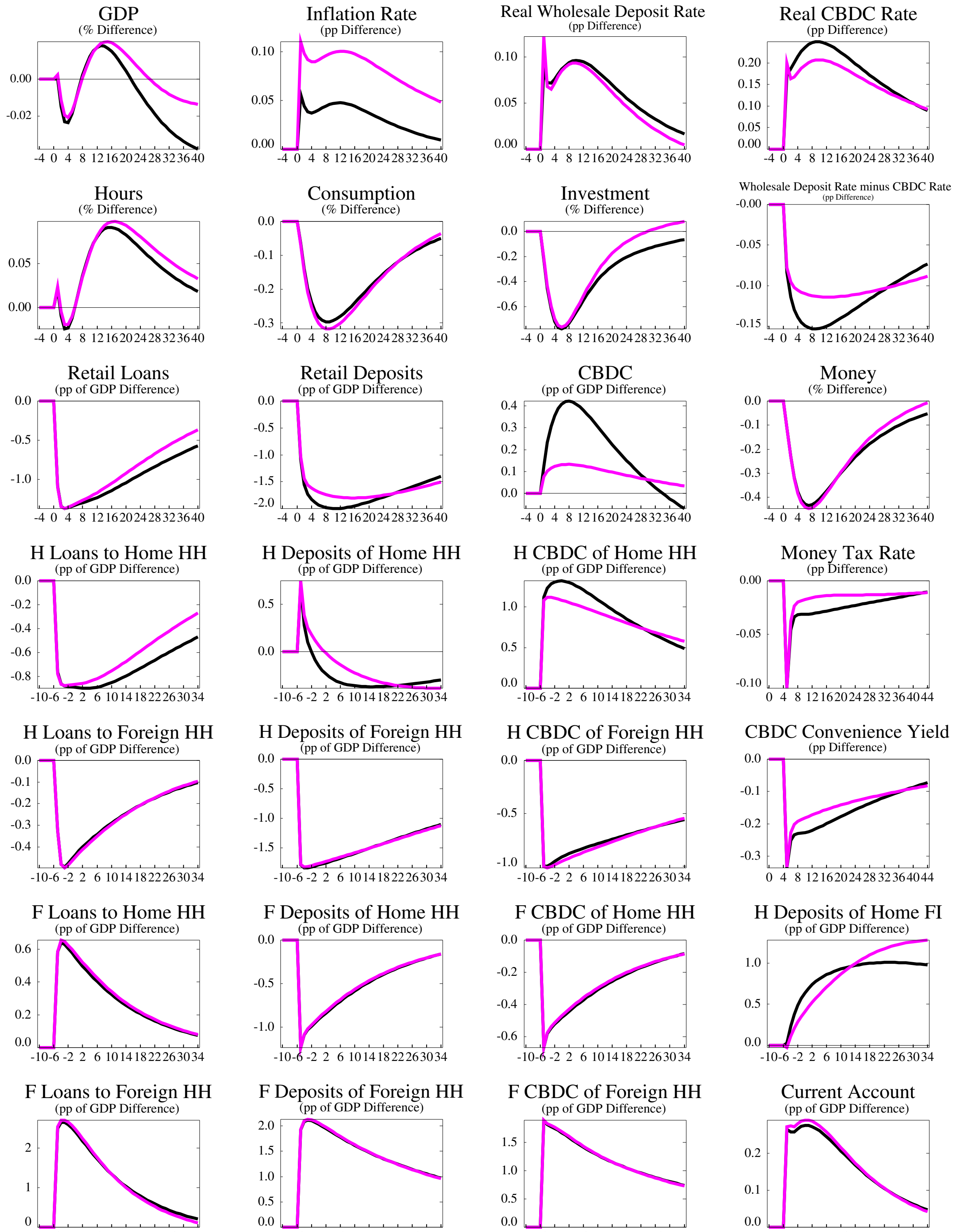
(black = INT-rule with optimized credit feedback,
pink = RES-rule with optimized credit feedback)

Figure 19. IRF - Interest Rate vs. Reserves Rules - Home Credit Supply



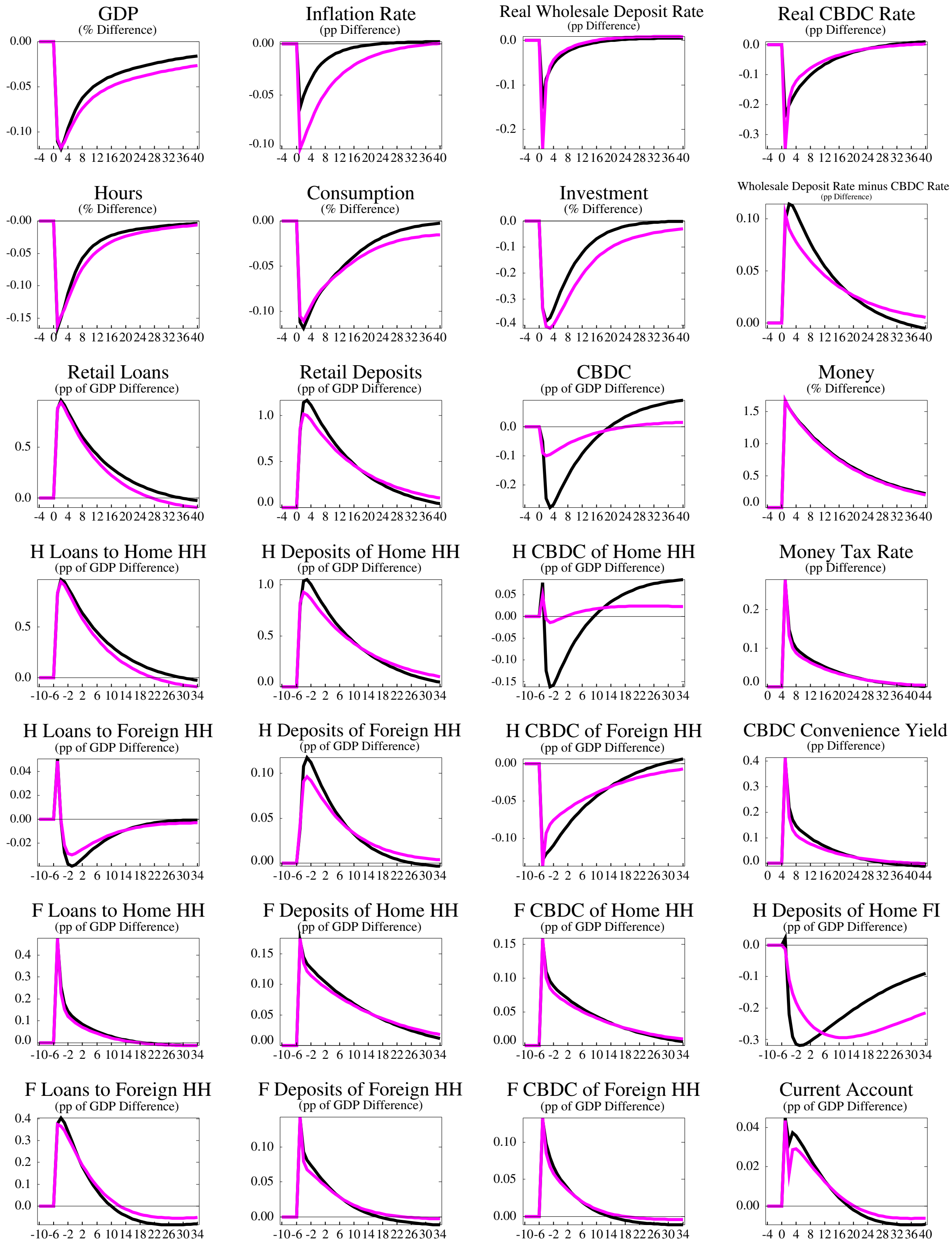
(black = INT-rule with optimized credit feedback,
pink = RES-rule with optimized credit feedback)

Figure 20. IRF - Interest Rate vs. Reserves Rules - Foreign Currency Demand



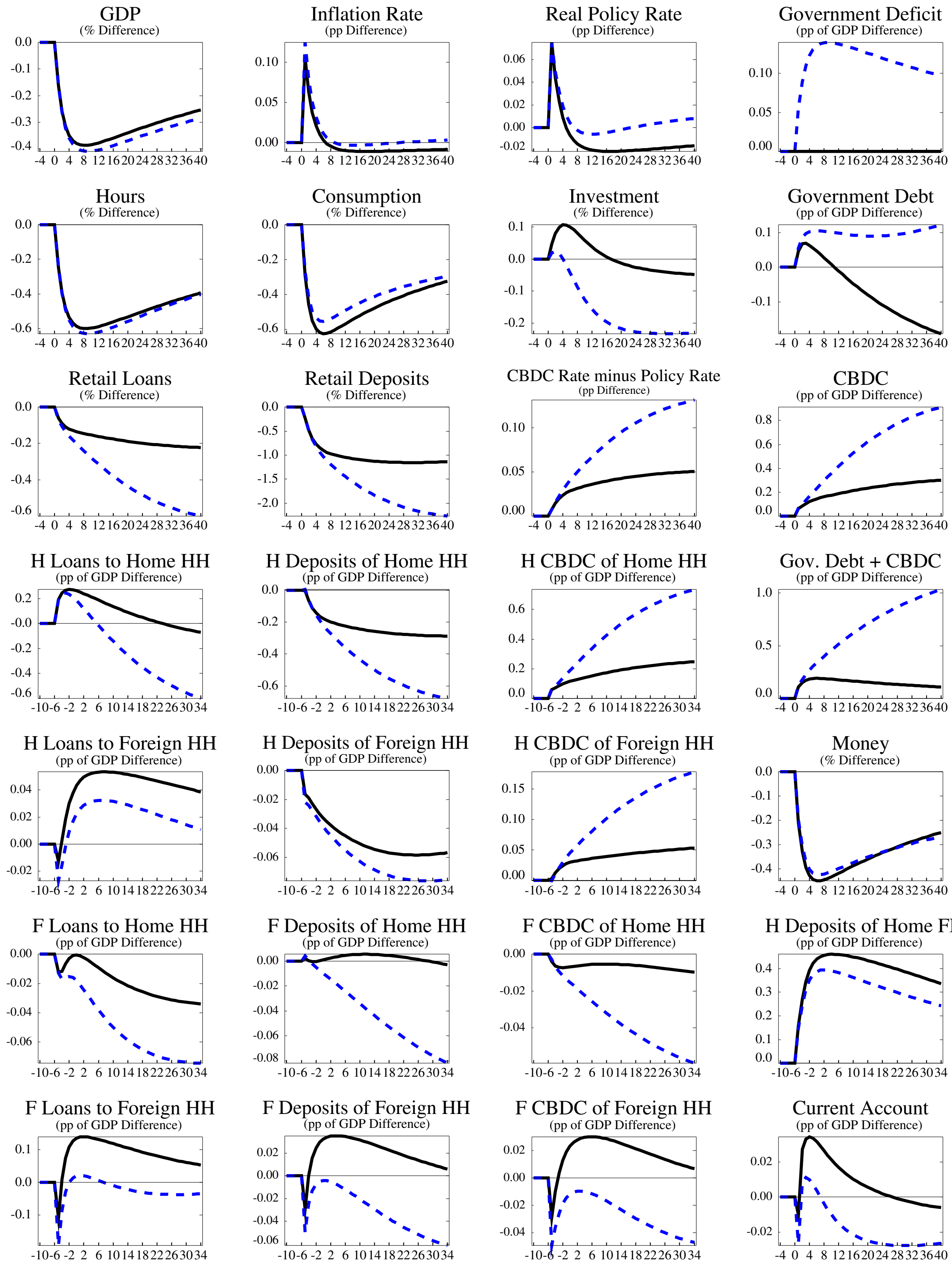
(black = INT-rule with optimized credit feedback,
pink = RES-rule with optimized credit feedback)

Figure 21. IRF - Interest Rate vs. Reserves Rules - Home Money Demand



(black = INT-rule with optimized credit feedback,
pink = RES-rule with optimized credit feedback)

Figure 22. IRF - Interest Rate Rule and Automatic Stabilizers - Home Consumption Demand



(black solid = INT-rule without automatic stabilizers,
blue dashed = INT-rule with automatic stabilizers)