# CBDCs, Financial Inclusion, and Optimal Monetary Policy*

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**Abstract**

This paper explores the interaction between monetary policy and financial inclusion with the introduction of a central bank digital currency (CBDC). Using a New Keynesian two-agent framework, we show that CBDCs can enhance welfare for unbanked households by providing an interest-bearing savings tool that facilitates consumption smoothing in response to monetary policy shocks. However, higher CBDC rates, while beneficial to unbanked households, reduce welfare for banked households due to tax redistribution effects. A Ramsey optimal policy exercise demonstrates that a social planner would typically set the CBDC rate to maintain a constant spread relative to the policy rate to maximise welfare. These findings emphasise the importance of tailoring CBDC design to an economy's level of financial inclusion.

**Keywords**: central bank digital currency, financial inclusion, optimal monetary policy, Taylor rules, welfare

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# 1 Introduction

Central bank digital currency (CBDC) is a form of digital money, denominated in the national unit of account, which is a direct liability of the central bank.[1] Central banks are actively studying the potential adoption of CBDCs; notable examples include Sweden's E-Krona and China's Digital Currency Electronic Payment. In this paper, we focus on the welfare implications of introducing a retail CBDC. We answer a number of macroeconomic questions on CBDC design: do CBDCs increase welfare of the unbanked through financial inclusion? Do they fundamentally change monetary policy transmission? Should a CBDC be interest bearing, and how should interest rates be optimally set?

We answer these questions using a two-agent New Keynesian (TANK) model with frictions in financial intermediation, and a central bank that sets interest rates on both deposits and the CBDC. Additionally, the two types of households in our model are referred to as the "banked" and "unbanked". Banked HH are akin to "unconstrained" households as in, for example, Galí, López-Salido, and Vallés (2007), Bilbiie (2018), and Debortoli and Galí (2017), and operate on their Euler equation due to having access to a non-state-contingent asset, bank deposits. Conversely, the unbanked can only smooth their consumption through real money balances and are subject to a cash-in-advance constraint. We then relax this restriction by allowing both the banked and unbanked households access to an interest-bearing CBDC.

Our analysis proceeds as follows. First, we examine the impact of a CBDC on the transmission of monetary policy, assuming that the central bank follows a standard Taylor rule and that the CBDC interest rate is aligned with the deposit rate. The introduction of a CBDC significantly influences the consumption patterns of unbanked households by providing them with access to an interest-bearing savings instrument, which allows these households to smooth consumption in response to monetary pol-

1. For more detail on the taxonomy of CBDC designs we refer readers to Auer and Böhme (2020). They discuss many aspects of CBDC design, such as whether the CBDC uses a distributed ledger technology (DLT), is account or token based, or wholesale or retail. In this paper we focus solely on retail CBDCs.

icy shocks. While output and consumption effects tend to dissipate more rapidly in an economy equipped with a CBDC, the persistence of monetary policy shocks on bank equity prices and net worth increases, highlighting a trade-off between macroeconomic and financial stability.

Second, we analyse the welfare and distributional effects of CBDC rates in comparison to deposit rates. Our findings indicate that unbanked households benefit when CBDC rates are higher than deposit rates, as the savings channel allows them to gain from higher interest rates on CBDC, providing a buffer against adverse shocks. For unbanked households, the advantages of using CBDC as a savings tool outweigh the issuance costs through taxation. Conversely, banked households experience a welfare decline when CBDC rates exceed the policy rate. This welfare loss arises primarily due to the tax redistribution effect: as CBDC rates rise, both banked and unbanked households shift toward holding more CBDC, funded by increased lump-sum taxes levied equally on all households. For banked households, the tax costs surpass the benefits of holding digital currency, leading to a net welfare loss. This outcome highlights the importance of tailoring CBDC rate design to the financial inclusion levels of an economy.

Third, we perform a Ramsey optimal policy analysis to determine the path of monetary policy that maximises household welfare. The social planner optimises a weighted average of banked and unbanked household welfare using two instruments: the central bank deposit rate and the CBDC interest rate. Our framework tests different CBDC policy regimes, such as adjustable versus fixed rates. We find that when CBDC closely substitutes regular deposits, the optimal policy is to maintain a constant spread between the CBDC rate and the policy rate. In economies with low financial inclusion, welfare gains are mainly due to the introduction of CBDC. In contrast, in economies with higher financial inclusion, the gains stem from optimal monetary policy. Notably, a single-instrument policy where the CBDC rate tracks the policy rate achieves welfare outcomes similar to those of a two-instrument policy.

**Related literature.** Our work relates to three strands of literature on CBDCs. First, we contribute to a literature understanding the benefits of introducing a CBDC (Chen et al., 2022).[2]

Our contribution is to show that the welfare effects depend crucially on the level of financial inclusion, with positive welfare effects on the unbanked through a CBDC increasing savings and acting as a consumption smoothing device.

Second, we contribute to the literature on the implications of CBDC adoption for financial stability (Brunnermeier and Niepelt, 2019; Fernández-Villaverde et al., 2021; Agur, Ari, and Dell'Ariccia, 2022; Andolfatto, 2021; Chiu et al., 2023; Keister and Sanches, 2021; Keister and Monnet, 2022; Hemingway, 2022; Bidder, Jackson, and Rottner, 2024). Key financial stability concerns include the competition between bank deposits and CBDCs. For instance, Chiu et al. (2023) examine how CBDCs can increase competition in the deposit market, potentially leading to a crowding in of bank deposits. In contrast, Keister and Sanches (2021) identify conditions where CBDC adoption could cause disintermediation in the private sector, resulting in welfare losses, while Bidder, Jackson, and Rottner (2024) explore the potential shift from deposits to CBDC during periods of financial stress.

While our model allows banks to substitute between deposits and CBDC, its primary contribution lies in highlighting the redistributive effects of CBDC introduction within a two-agent framework. Importantly, we find that a CBDC can enhance welfare, improve financial inclusion, and reduce consumption inequality.

Finally, we contribute to a growing literature that deals with the closed economy (Burlon et al., 2022; Davoodalhosseini, 2022; Das et al., 2023; Barrdear and Kumhof, 2022; Assenmacher, Bitter, and Ristiniemi, 2023; Abad, Nuño Barrau, and Thomas, 2023; Bhattarai, Davoodalhosseini, and Zhao, 2024) and open economy macroeconomic implications of introducing a CBDC (Ikeda, 2020; Kumhof et al., 2021; Minesso, Mehl, and Stracca, 2022). This includes a discussion of optimal monetary policy and trans-

2. These studies include the potential for CBDCs to address financial inclusion in emerging market economies such as India and Nigeria, which have a large unbanked population and increasing reliance on digital payments and private payment providers, and theoretical models of financial inclusion in an economy with competition between different types of payments.

mission effects, the use of CBDC in a monetarist framework, and the introduction of CBDC on output and the ability to stabilise business cycle fluctuations.

Our contribution is to show the transmission of monetary policy and derive the optimal path of interest rates when the central bank controls two instruments: the interest rate on deposits and the CBDC interest rate. The welfare effects on banked and unbanked agents depend crucially on whether the CBDC is interest bearing, and through a Ramsey optimal policy exercise we show that CBDC rates should target a constant spread with respect to the policy rate.

The remainder of the paper is structured as follows. In Section 2, we setup the TANK model and state our modelling assumptions. Section 3 examines the effect of introducing a CBDC on monetary policy, including optimal policy exercises for when a social planner can set interest rates on deposits and the CBDC, and examines the welfare implications of alternative rules for targeting the interest rate on the CBDC. Section 4 concludes the paper.

## 2 Two-Agent New Keynesian Model with Central Bank Digital Currency

In this section, we present a two-agent New Keynesian (TANK) model as in Debortoli and Galí (2017, 2022) and Bilbiie (2018). Notably, our model features a banking sector accompanied with credit frictions (Gertler and Karadi, 2011; Gertler and Kiyotaki, 2010). In this framework, a fixed fraction of the banked HH are bankers, which allows us to maintain a representative setup of the household sector. Banked HH hold claims on CBDC and deposits. Deposits are denominated in fiat currency and held at banks. Banked HH may also directly invest in firms by purchasing equity holdings. Banks convert deposits into credit, facilitating loans to firms who acquire capital for the means of production, as in Gertler and Kiyotaki (2010, 2015). Unbanked HH are still limited to money holdings and CBDCs.

## 2.1 Production

The supply side of the economy is standard. Final goods are produced by perfectly competitive firms that use labour and capital to produce their output.[3] They also have access to bank loans, and conditional on being able to take out a loan, they do not face any financial frictions. These firms pay back the crediting banks in full via profits. Meanwhile, capital goods are produced by perfectly competitive firms, which are owned by the collective household.

**Capital good firms.** We assume that capital goods are produced by perfectly competitive firms, and that the aggregate capital stock grows according to the following law of motion:

$$K_t = I_t + (1-\delta)K_{t-1}, \tag{1}$$

where $I_t$ is investment and $\delta \in (0,1)$ is the depreciation rate.

The objective of the capital good producing firm is to choose $I_t$ to maximise revenue, $Q_t I_t$. Thus, the representative capital good producing firm's objective function is:

$$\max_{I_t} \left\{ Q_t I_t - I_t - \Phi\left(\frac{I_t}{I}\right) I_t \right\},$$

where $\Phi(\cdot)$ are investment adjustment costs and are defined as:

$$\Phi\left(\frac{I_t}{I}\right) = \frac{\kappa_I}{2}\left(\frac{I_t}{I} - 1\right)^2,$$

with $\Phi(1) = \Phi'(1) = 0$ and $\Phi''(\cdot) > 0$.

**Intermediate goods producers.** The continuum of intermediate good producers are normalised to have a mass of unity. A typical intermediate firm produces output $y_t$ according to a constant returns to scale technology in capital $k_t$ and labour $l_t$ with a common productivity shock $A_t$

$$y_t = A_t k_{t-1}^{\alpha} l_t^{1-\alpha}.$$

3. We relegate the discussion of final good firms to the Appendix A.1.1 as it is standard.

The problem for an intermediate firm is to minimise costs subject to their production constraint, where the demand for their output is given by the standard index:

$$y_t = \left(\frac{p_t}{P_t}\right)^{-\epsilon} Y_t.$$

This yields the minimised unit cost of production:

$$MC_t = \frac{1}{A_t}\left(\frac{z_t^k}{\alpha}\right)^{\alpha}\left(\frac{w_t}{1-\alpha}\right)^{1-\alpha}. \tag{2}$$

The price-setting problem of a firm is set up à la Rotemberg (1982) where it maximises the net present value of profits,

$$\mathbb{E}_t \sum_{s=0}^{\infty} \Lambda^h_{t,t+s}\left[\left(\frac{p_{t+s}}{P_{t+s}}(1-\tau) - MC_{t+s}\right) y_{t+s} - \frac{\kappa}{2}\left(\frac{p_{t+s}}{p_{t-1+s}} - 1\right)^2 Y_{t+s}\right],$$

by optimally choosing $p_t$, and where $\kappa$ denotes a price adjustment cost parameter for the firms.

Evaluating at the symmetric equilibrium where intermediate firms optimally price their output at $p_t = P_t, \forall i$, yields the standard New Keynesian Phillips curve (NKPC):

$$\pi_t(\pi_t - 1) = \frac{\epsilon - 1}{\kappa}\left(\mathcal{M}_t MC_t + \tau - 1\right) + \mathbb{E}_t \Lambda^h_{t,t+1}(\pi_{t+1} - 1)\pi_{t+1}\frac{Y_{t+1}}{Y_t}, \tag{3}$$

where $\mathcal{M}_t$ is the representative intermediate firm's markup.

Also, under the symmetric equilibrium we can express output as:

$$Y_t = A_t K^{\alpha}_{t-1} L_t^{1-\alpha}. \tag{4}$$

As noted above, there is a distortion arising from monopolistic competition among intermediate firms. We assume that there is a lump-sum subsidy to offset this distortion, $\tau$. From (3), we see that the policymaker chooses a subsidy such that the markup over marginal cost is offset in the deterministic steady state:[4]

$$\tau = -\frac{1}{\epsilon - 1}$$

which guarantees a non-distorted steady-state. Hereinafter, we abstract from distorted steady states and only consider the efficient steady state. Our choice to model nominal rigidity following Rotemberg pricing should not alter our welfare analysis in Section 3. As noted by Nisticò (2007) and Ascari and Rossi (2012), up to a second order approximation and provided that the steady state is efficient, models under both Calvo

4. Note that this assumes that steady state inflation is net-zero, i.e., $\pi = 1$.

and Rotemberg pricing imply the same welfare costs of inflation. Therefore, a welfare-maximising social planner would prescribe the same optimal policy across the two regimes.

## 2.2 Households and Workers

The representative household contains a continuum of individuals, normalised to 1, each of which are of type $i \in \{h, u\}$. Bankers and banked workers ($i = h$) share a perfect insurance scheme, such that they each consume the same amount of real output. However, unbanked workers ($i = u$) are not part of this insurance scheme, and so their consumption volumes are different from bankers and workers. We define $\Gamma_h$ as the proportion of the BHH and bankers, and the UHH are of proportion $\Gamma_u = 1 - \Gamma_h$.

We endogenise labour supply decisions on the part of households, and so the BHH maximises the present value discounted sum of utility:[5]

$$\mathbb{V}_t^h = \max_{\{C_{t+s}^h, L_{t+s}^h, D_{t+s}, K_{t+s}^h, DC_{t+s}^h\}_{s=0}^{\infty}} \mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \Xi_{t+s} \ln \left( C_{t+s}^h - \zeta_0^h \frac{(L_{t+s}^h)^{1+\zeta}}{1+\zeta} \right), \tag{5}$$

subject to their period budget constraint:

$$\begin{aligned} C_t^h + D_t + Q_t K_t^h + \chi_t^h + DC_t^h + \chi_t^{DC,h} + T_t^h \\ = w_t L_t^h + \Pi_t + R_t^k Q_{t-1} K_{t-1}^h + \frac{R_{t-1} D_{t-1} + R_{t-1}^{DC} DC_{t-1}^h}{\pi_t}, \end{aligned} \tag{6}$$

where $w_t$ are real wages, $L_t^i$ is labour supply, $R_t^k = (z_t^k + (1-\delta)Q_t)/Q_{t-1}$ is the gross return on equity or capital, $\zeta$ is the inverse-Frisch elasticity of labour supply, $\zeta_0^i$ is a relative labour supply parameter, $K_t^h$ are equity holdings in firms by the BHH, $\chi_t^h$ are the costs of equity acquisitions incurred by the BHH, $\chi_t^{DC,i}$ are digital currency management costs,[6] $T_t^i$ are lump-sum taxes, $Q_t$ is the price of equity/capital, and $\Pi_t$ are

5. We make use of Greenwood–Hercowitz–Huffman preferences for both the BHH and UHH to eliminate the income effect on an agent's labour supply decision. Additionally, it allows us to develop a tractable analytical solution for the model steady state.

6. The digital currency management costs for household of type $i$ are:

$$\chi_t^{DC,i} = \frac{\varkappa^{DC}}{2} \left( \frac{DC_t^i}{\widetilde{DC}^i} \right)^2, \quad i \in \{h, u\},$$

where $\widetilde{DC}^i$ are target digital currency balances, calibrated in the baseline case such that aggregate holding of digital currencies is one-third of output. Alternatively, we could assume a non-pecuniary motive for holding digital currency that would manifest as an additional term of the same form in the household utility function. This setup would imply the same first-order conditions.

distribution of profits due to the ownership of banks and firms. There is a shock to agents' preferences, $\Xi_t$, and it is given by:

$$\Xi_{t+s} = \begin{cases} e^{\xi_1} e^{\xi_2} ... e^{\xi_s} & \text{for } s \geq 1, \\ 1 & \text{for } s = 0, \end{cases}$$

where $\xi_t$ is a preference (demand) shock given by an AR(1) process. We also note that $\Lambda^h_{t,t+s}$ is the BHH stochastic discount factor (SDF):

$$\Lambda^h_{t,t+s} \equiv \beta^s \mathbb{E}_t \frac{\Xi_{t+s} \lambda^h_{t+s}}{\lambda^h_t}, \tag{7}$$

where $\lambda^h_t$ is the marginal utility of consumption for the BHH.

One distinction between banked workers and bankers purchasing equity in firms is the assumption that the worker pays an efficiency cost, $\chi^h_t$, when they adjust their equity holdings. We assume the following functional form for $\chi^h_t$:

$$\chi^h_t = \frac{\varkappa^h}{2} \left( \frac{K^h_t}{K_t} \right)^2 \Gamma_h K_t. \tag{8}$$

Meanwhile, the UHH maximises the present discounted sum of per-period utilities given by:

$$\mathbb{V}^u_t = \max_{\{C^u_{t+s}, L^u_{t+s}, M_{t+s}, DC^u_{t+s}\}^{\infty}_{s=0}} \mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \Xi_{t+s} \ln \left( C^u_t - \zeta^u_0 \frac{(L^u_t)^{1+\zeta}}{1+\zeta} \right), \tag{9}$$

subject to its budget constraint,

$$C^u_t + M_t + \chi^M_t + DC^u_t + \chi^{DC,u}_t + T^u_t = w_t L^u_t + \frac{M_{t-1} + R^{DC}_{t-1} DC^u_{t-1}}{\pi_t}, \tag{10}$$

and the CIA constraint,

$$\alpha_M C^u_t \leq \frac{M_{t-1}}{\pi_t}. \tag{11}$$

## 2.3 Banks

Bankers are indexed on the continuum $j \in [0, 1]$. Among the population of bankers, each $j$-th banker owns and operates their own bank which has a continuation probability given by $\sigma_b$. A banker will facilitate financial services between households and firms by providing loans to firms in the form of equity, $k^b_t$, funded by deposits, $d_t$, and their own net worth, $n_t$.

As is standard in the literature, bankers face a balance sheet constraint:

$$Q_t k_t^b = d_t + n_t, \tag{12}$$

and a flow of funds constraint:

$$n_t = R_t^k Q_{t-1} k_{t-1}^b - \frac{R_{t-1}}{\pi_t} d_{t-1}, \tag{13}$$

where net worth is the difference between gross return on assets and liabilities. Note that for the case of a new banker, the net worth is the startup fund given by the collective household by fraction $\gamma_b$:

$$n_t = \gamma_b R_t^k Q_{t-1} k_{t-1}.$$

The objective of a banker is to maximise franchise value, $\mathbb{V}_t^b$, which is the expected present discount value of terminal wealth:

$$\mathbb{V}_t^b = \mathbb{E}_t \left[ \sum_{s=1}^{\infty} \Lambda_{t,t+s}^h \sigma_b^{s-1} (1-\sigma_b) n_{t+s} \right]. \tag{14}$$

A financial friction in line with Gertler and Kiyotaki (2010) and Gertler and Karadi (2011) is used to limit the banker's ability to raise funds from depositors, whereby the banker faces a moral hazard problem: the banker can either abscond with the funds they have raised from depositors, or the banker can operate honestly and pay out their obligations. Absconding is costly, however, and so the banker can only divert a fraction $\theta^b > 0$ of assets they have accumulated.[7] Thus, bankers face the following incentive compatibility constraint:

$$\mathbb{V}_t^b \geq \theta^b Q_t k_t^b. \tag{15}$$

The problem of the banker consists of maximising (14) subject to the balance sheet constraint (12), the evolution of net worth (13), and the incentive compatibility constraint (15).

Since $\mathbb{V}_t^b$ is the franchise value of the bank, which we can interpret as a "market value", we can divide $\mathbb{V}_t^b$ by the bank's net worth to obtain a Tobin's Q ratio for the bank denoted by $\psi_t$:

$$\psi_t \equiv \frac{\mathbb{V}_t^b}{n_t} = \mathbb{E}_t \Lambda_{t,t+1}^h (1 - \sigma_b + \sigma_b \psi_{t+1}) \frac{n_{t+1}}{n_t}. \tag{16}$$

7. It is assumed that the depositors act rationally and that no rational depositor will supply funds to the bank if they clearly have an incentive to abscond.

We define $\phi_t$ as the maximum feasible asset to net worth ratio, or, rather, the leverage ratio of a bank:

$$\phi_t = \frac{Q_t k_t^b}{n_t}. \tag{17}$$

Additionally, if we define $\Omega_{t,t+1}$ as the stochastic discount factor of the banker, $\mu_t$ as the excess return on capital over fiat currency deposits, and $\upsilon_t$ as the marginal cost of deposits, we can write the banker's problem as the following:

$$\psi_t = \max_{\phi_t} \left\{ \mu_t \phi_t + \upsilon_t \right\}, \tag{18}$$

subject to

$$\psi_t \geq \theta^b \phi_t.$$

Solving this problem yields:

$$\psi_t = \theta^b \phi_t, \tag{19}$$

$$\phi_t = \frac{\upsilon_t}{\theta^b - \mu_t}, \tag{20}$$

where:

$$\mu_t = \mathbb{E}_t \Omega_{t,t+1} \left( R_{t+1}^k - \frac{R_t}{\pi_{t+1}} \right), \tag{21}$$

$$\upsilon_t = \mathbb{E}_t \Omega_{t,t+1} \frac{R_t}{\pi_{t+1}}, \tag{22}$$

$$\Omega_{t,t+1} = \Lambda_{t,t+1}^h (1 - \sigma_b + \sigma_b \psi_{t+1}). \tag{23}$$

For a complete solution of the banker, please refer to Appendix A.1.3 and A.1.4.

## 2.4 Fiscal and Monetary Policy

We assume that the government operates a balanced budget:

$$\frac{R_{t-1}^{DC}}{\pi_t} DC_{t-1} + \frac{M_{t-1}}{\pi_t} = \tau Y_t + \Gamma_h T_t^h + \Gamma_u T_t^u + DC_t + M_t, \tag{24}$$

where it levies taxes to cover the producer subsidy to address the distortions arising from monopolistic competition, money balances, and digital currencies. Our budget constraint allows for money and digital currency to be a liability of the central bank, and is consistent with other studies that model the issuance of CBDC (Barrdear and Kumhof, 2022; Kumhof et al., 2021).

Meanwhile, the central bank is assumed to operate an inertial Taylor rule for the nominal interest rate:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi} \left(\frac{Y_t}{Y}\right)^{\phi_Y}\right]^{1-\rho_R} \exp(\varepsilon_t^R), \tag{25}$$

where variables without time subscripts denote steady state values. Additionally, we assume that the central bank sets the nominal return on digital currency one-for-one in line with the nominal interest rate on deposits:

$$R_t^{DC} = R_t. \tag{26}$$

We explore the implications of alternative rules on model dynamics and welfare in Section 3.

## 2.5 Market Equilibrium

Aggregate consumption, labour supply, and digital currency holdings by the BHH and UHH are given as:

$$C_t = \Gamma_h C_t^h + \Gamma_u C_t^u, \tag{27}$$

$$L_t = \Gamma_h L_t^h + \Gamma_u L_t^u, \tag{28}$$

$$DC_t = \Gamma_h DC_t^h + \Gamma_u DC_t^u. \tag{29}$$

Then define $\omega_t$ as the consumption inequality factor, as in Debortoli and Galí (2017), between the banked and unbanked households:

$$\omega_t = 1 - \frac{C_t^u}{C_t^h}. \tag{30}$$

This will allow us to track consumption inequality between the two types of households. Increases (decreases) in $\omega_t$ indicate that banked households are consuming a larger (smaller) share of aggregate consumption.

The aggregate resource constraint of the economy is:

$$Y_t = C_t + \left[1 + \Phi\left(\frac{I_t}{I}\right)\right] I_t + \frac{\kappa}{2}(\pi_t - 1)^2 Y_t + \Gamma_h(\chi_t^h + \chi_t^{DC,h}) + \Gamma_u(\chi_t^M + \chi_t^{DC,u}), \tag{31}$$

with aggregate capital being given by:

$$K_t = \Gamma_h(K_t^h + K_t^b). \tag{32}$$

Aggregate net worth of the bank is given by:

$$N_t = \sigma_b \left( R_t^k Q_{t-1} K_{t-1}^b - \frac{R_{t-1}}{\pi_t} D_{t-1} \right) + \gamma_b R_t^k Q_{t-1} \frac{K_{t-1}}{\Gamma_h}, \tag{33}$$

and the aggregate balance sheet of the bank is given by the following equations:

$$Q_t K_t^b = \phi_t N_t, \tag{34}$$

$$Q_t K_t^b = D_t + N_t. \tag{35}$$

Finally, the stationary AR(1) processes for TFP, markup, and preference shocks are given by:

$$\ln A_t = \rho_A \ln A_{t-1} + \varepsilon_t^A, \tag{36}$$

$$\mathcal{M}_t = (1 - \rho_M)\mathcal{M} + \rho_M \mathcal{M}_{t-1} + \varepsilon_t^M, \tag{37}$$

$$\xi_t = \rho_\xi \xi_{t-1} + \varepsilon_t^\xi \tag{38}$$

A competitive equilibrium is a set of eight prices, $\{ MC_t, R_t, R_t^{DC}, R_t^k, \pi_t, Q_t, w_t, z_t^k \}$, nineteen quantity variables, $\{ C_t, C_t^h, C_t^u, D_t, DC_t, DC_t^h, DC_t^u, I_t, K_t, K_t^b, K_t^h, L_t, L_t^h, L_t^u, M_t, N_t, T_t^h, T_t^u, Y_t \}$, four bank variables, $\{ \psi_t, \phi_t, \mu_t, \upsilon_t \}$, and three exogenous variables, $\{ A_t, \xi_t, \mathcal{M}_t \}$, that satisfies 34 equations. For a complete list of the equilibrium conditions please refer to Appendix A.1.5. Steady state solutions are provided in Appendix A.1.6 for the baseline TANK model.

## 2.6 Model Calibration and Steady State Values

We set model parameters, which are found in standard New Keynesian models, in line with the literature. See, for example, Galí (2015), Walsh (2010), and Woodford (2003). Parameter values are provided in Table 1.

Model parameters that are not standard, particularly those related to the banking sector, are based on Akinci and Queralto (2022). For instance, the banker's survival rate, $\sigma_b$, is set so that the annual dividend payout equals $4 \times (1 - \sigma_b) = 0.24$ of net worth. The banker absconding ratio, $\theta^b$; the banker management cost of digital currencies, $\varkappa^b$; and the fraction of total assets inherited by new bankers, $\gamma^b$, are calibrated to ensure that in steady state, the bank leverage ratio is approximately 4, and the share of equity

Table 1: **Parameter values**

| | | |
|---|---|---|
| $\theta^b$ | 0.399 | Banker absconding ratio |
| $\sigma_b$ | 0.940 | Survival probability |
| $\gamma^b$ | 0.005 | Fraction of total assets inherited by new banks |
| $DC/4Y$ | 1/3 | DC to Output |
| $\beta$ | 0.990 | Discount rate |
| $\zeta$ | 0.333 | Inverse-Frisch elasticity |
| $\zeta_0^h$ | 3.050 | Labour supply disutility |
| $\varkappa^h$ | 0.020 | Cost parameter of direct finance |
| $\Gamma_h$ | 0.750 | Proportion of BHH |
| $\alpha_M$ | 1 | Inverse velocity of money |
| $\phi_M$ | 0.010 | Money adjustment cost parameter |
| $\varkappa^{DC}$ | 0.001 | Digital currency adjustment cost parameter |
| $\alpha$ | 0.333 | Capital share of output |
| $\delta$ | 0.025 | Depreciation rate |
| $\epsilon$ | 10 | Elasticity of demand |
| $\kappa_I$ | 2/3 | Investment adjustment cost |
| $\theta$ | 0.750 | Calvo parameter |
| $\tau$ | 0.111 | Producer subsidy |
| $\mathcal{M}$ | 1.111 | Markup |
| $\phi_\pi$ | 2 | Taylor rule inflation coefficient |
| $\phi_Y$ | 0.100 | Taylor rule output coefficient |
| $\rho_b$ | 0.850 | AR(1) coefficient for demand shock |
| $\rho_A$ | 0.850 | AR(1) coefficient for TFP shock |
| $\rho_M$ | 0.850 | AR(1) coefficient for markup shock |
| $\rho_R$ | 0.550 | Taylor rule persistence |
| $\sigma^A$ | 0.5% | TFP std dev |
| $\sigma^D$ | 0.1% | Demand shock std dev |
| $\sigma^M$ | 1% | Markup shock std dev |
| $\sigma^R$ | 0.5% | MP shock std dev |

financed by bank finance is about 70%.

Additionally, parameters related to the adjustment costs of money balances, $\phi_M$, and CBDCs, $\varkappa^{DC}$, are calibrated so that digital currency is more easily adjustable than money balances, with deposits being the preferred vehicle for transactions and savings. Our results remain robust across different calibrations of these parameters, as long as $0 < \varkappa^{DC} < \phi_M$. We calibrate $\widetilde{DC}$ so that the CBDC-to-output ratio is approximately one-third, which aligns with the baseline calibration in Barrdear and Kumhof (2022) and Kumhof et al. (2021), resulting in a CBDC-to-total-assets ratio of about 14%, similar to estimates reported in Assenmacher, Bitter, and Ristiniemi (2023).

Lastly, the parameters related to monetary policy—namely, the sensitivity of nominal interest rates to inflation, $\phi_\pi$, the sensitivity to the output gap, $\phi_Y$, and the interest rate smoothing parameter, $\rho_R$—are set in accordance with Guerrieri and Iacoviello (2015). The persistence of our exogenous AR(1) processes is assumed to be 0.85 per quarter. Standard deviations of shocks are set at 0.5% per quarter for TFP and 0.1% for cost-push, preference, and monetary policy shocks, unless stated otherwise. For example, innovations to shocks are set at 1% when plotting impulse response functions.

# 3 Dynamics and Welfare Implications

## 3.1 Impulse Responses to a Monetary Policy shock

Figure 1 presents impulse responses to a 1% (annualised) monetary policy tightening with the Taylor rule (25) and $R_t = R_t^{DC}$.[8] We plot impulse responses for two alternative regimes: a CBDC-equipped economy as described in Section 2 (red dashed line) and an economy with no CBDCs (blue line).

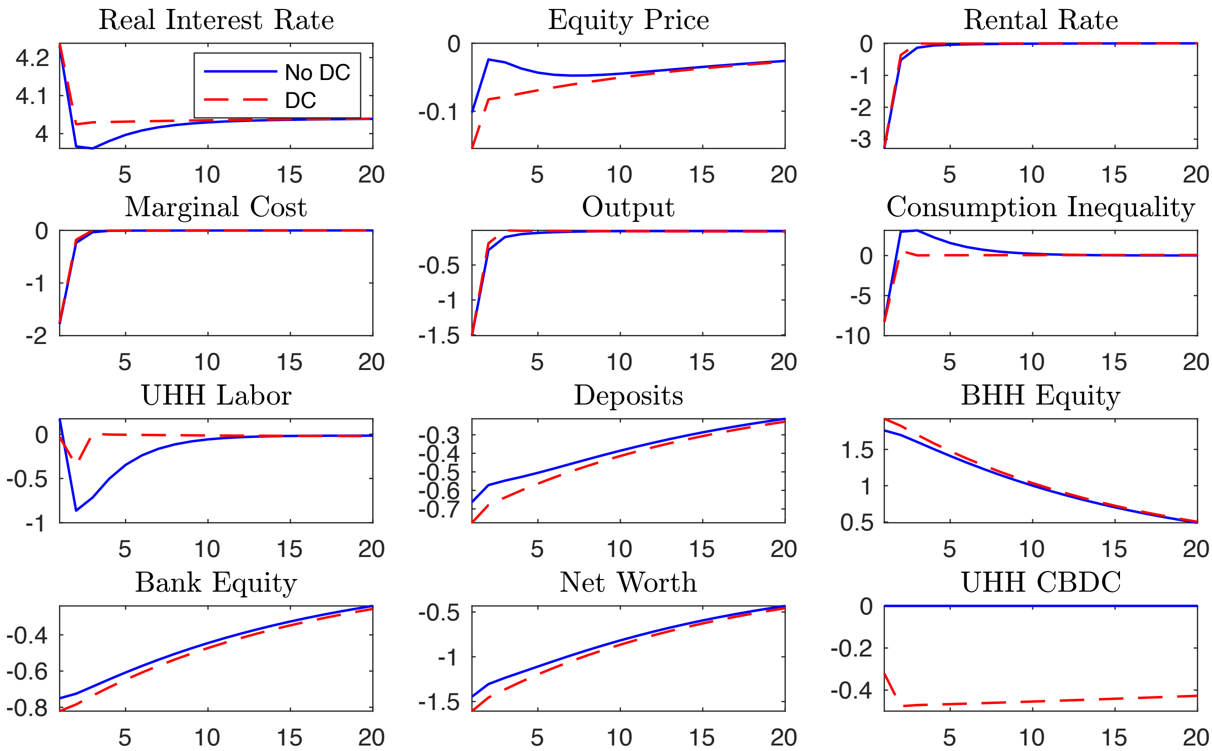
Under the no-DC regime, the monetary policy tightening has standard responses for the real economy: output, consumption, and the marginal cost decline in response to the increase in the real interest rate. Here consumption inequality ($\omega$) initially improves as the unbanked HH benefits from the deflationary pressure in the economy, increasing real money balances.[9] The impact on financial variables are also in line with DSGE models with financial intermediation (see for example Gertler and Kiyotaki (2010) and Gertler and Karadi (2011)): A small decline in the price of equity leads to a decline in bank intermediation as bank equity, deposits, and net worth shrinks, affecting the real economy via the financial accelerator mechanism (Kiyotaki and Moore, 1997; Bernanke, Gertler, and Gilchrist, 1999).

The presence of a CBDC significantly changes the dynamics of the economy, primarily because it allows unbanked households to better smooth their consumption. Without a CBDC, unbanked households must drastically cut consumption when re-

8. A full set of IRFs can be found in Appendix A.2, and Figure 10 plots the impulse responses to the monetary policy tightening for a broader set of model variables.

9. For brevity, we avoid plotting wages, the banked HH labour supply, and the banked HH consumption as they are highly correlated with output due to the specification of GHH preferences and operating on a standard consumption Euler equation.

Figure 1: **IRFs to a 1% annualised monetary policy (tightening) shock**




Note: Figure plots impulse responses of model variables with respect to a 1% annualised innovation to the Nominal Interest Rate. Time periods are measured in quarters, and responses are measured as a percent deviation from steady state except for Inflation ($\pi$) and Nominal Interest Rates ($R$) which are expressed as annualised net rates.

lying solely on real money balances as a savings vehicle. However, with a CBDC, these households can absorb shocks more effectively by reducing their CBDC holdings, which helps to mitigate the drop in consumption. For banked households, the introduction of a CBDC has little impact on their consumption response, as they already have access to bank deposits and do not significantly adjust their CBDC holdings.

We note a trade-off between macroeconomic and financial stability in response to monetary policy shocks. While the introduction of a CBDC reduces the impact on consumption and output, leading to quicker dissipation of monetary shocks and greater stabilisation of output, consumption, and returns on capital, it also causes more persistent declines in bank-related variables, such as net worth and equity, driven by equity price dynamics and the financial accelerator effect.

Table 2: Model simulated standard deviations (%)

| | no-CBDC | CBDC |
|---|---|---|
| Output, $Y$ | 2.39 | 2.51 |
| Inflation, $\pi$ | 1.51 | 1.44 |
| Nominal Interest Rate, $R$ | 2.04 | 1.90 |
| Net Worth, $N$ | 6.68 | 6.57 |
| Bank Leverage, $\phi$ | 1.81 | 1.73 |

Note: Standard deviations are conditional standard deviations based on model simulations. The model is solved and simulated via second-order perturbation about the deterministic steady state. Inflation and the Nominal Interest Rate are annualised.

#### 3.1.1 Macroeconomic vs Financial Stability trade-offs

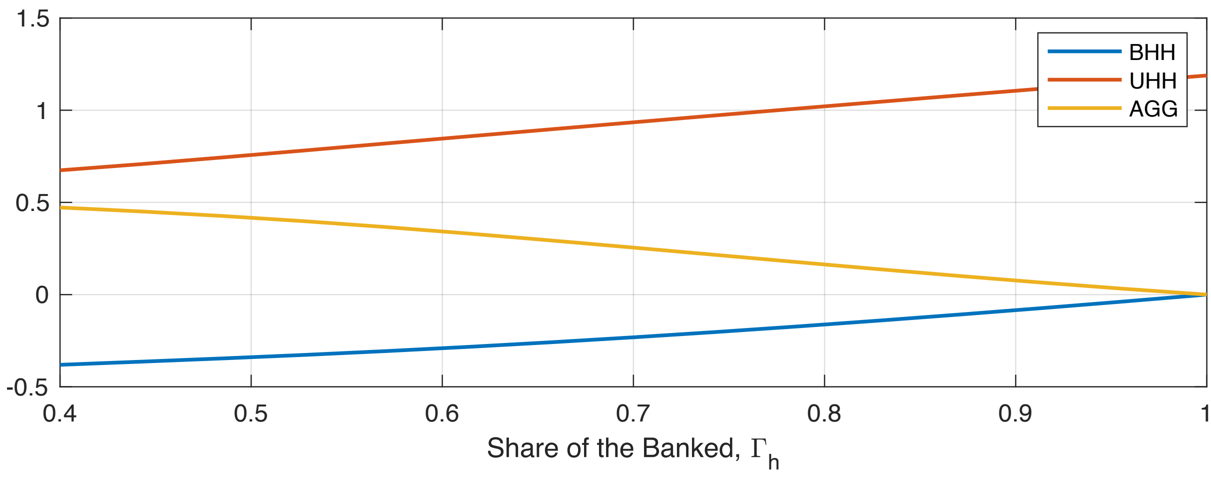
In addition to the analysis of monetary policy shocks, we now simulate both the no-CBDC and CBDC economies to capture the conditional standard deviations of key macroeconomic and financial variables when the model is subject to all shocks in the economy: this includes monetary, cost-push, demand and TFP shocks. [10] The results are summarised in Table 2.

While the introduction of a CBDC stabilises inflation, the policy rate, and bank financial variables, it slightly increases output volatility compared to the no-CBDC economy. This increased volatility is primarily due to changes in the consumption patterns of unbanked households when they have access to CBDCs.

In the no-CBDC economy, unbanked household consumption is procyclical in response to cost-push, demand, and monetary policy shocks, but countercyclical with respect to TFP shocks. However, with the introduction of CBDCs, unbanked household consumption becomes procyclical in response to TFP shocks. While output volatility is reduced for monetary shocks, the strong procyclicality of unbanked consumption in response to TFP shocks dominates, resulting in higher output volatility in the CBDC economy.

10. For IRF of output to cost-push, demand and TFP shocks, we refer readers to Appendix A.2.

Figure 2: **Welfare comparison (CBDC regime %ch. over no-CBDC regime)**




Note: Figure plots welfare for BHH, UHH and aggregate households as a function of the share of the banked population, $\Gamma_h$. The welfare is calculated as a per cent change from the regime with no digital currency.

## 3.2 Welfare Effects

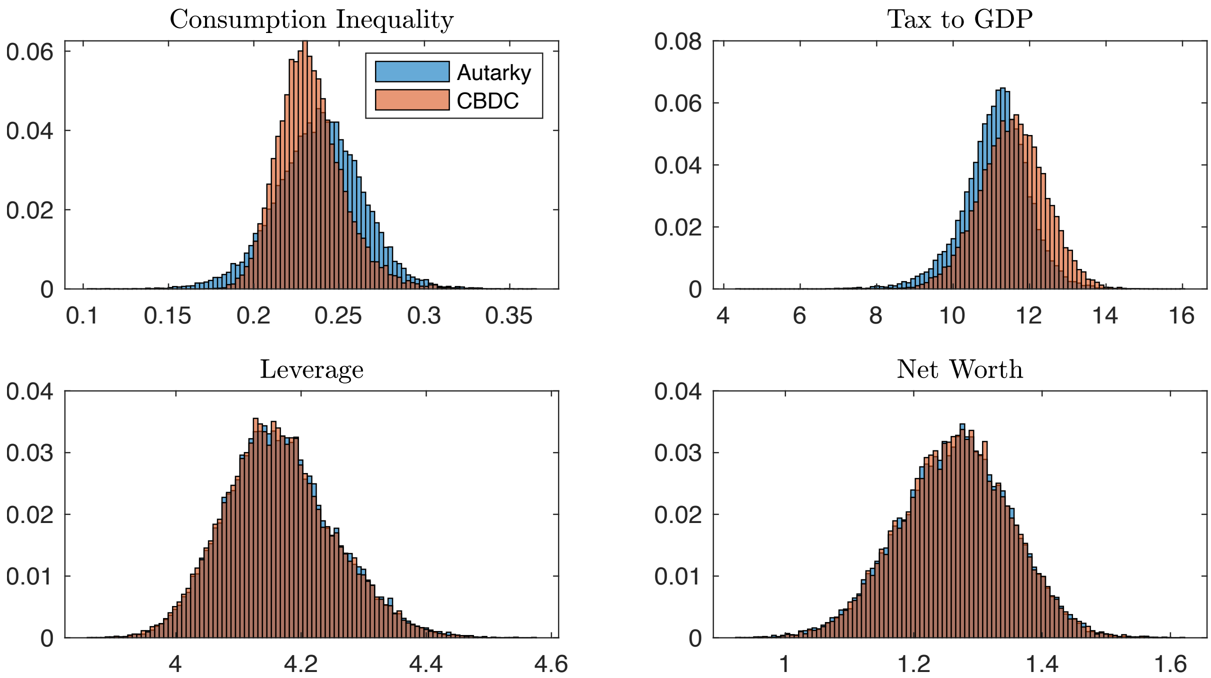
### 3.2.1 CBDC introduction

Figure 2 evaluates the welfare effects of introducing a CBDC when the economy is subject to TFP, cost-push, demand, and monetary policy shocks, with monetary policy conducted according to the Taylor rule (25). The results show that unbanked households experience welfare gains in the CBDC-equipped economy. This is primarily because the CBDC offers a rate of remuneration and serves as a more efficient savings device than money balances, enabling the unbanked to better insure against adverse shocks.

In contrast, banked households experience net negative welfare effects following the introduction of the CBDC. Aggregate welfare benefits are highest when the economy has a large unbanked population, but as the proportion of unbanked households declines, the welfare benefits of introducing CBDC tend to zero. This suggests that CBDCs may have a stronger use case in emerging markets with lower degrees of financial inclusion.

To explain these distributional effects, we note two key factors. First, banked households face management costs in holding CBDCs relative to bank deposits, and therefore do not gain as much from access to a CBDC, since they already have access to bank

Figure 3: **Simulations of consumption inequality, tax-to-output ratio, bank leverage and net worth: CBDC and autarky regimes**




Note: Plot of simulations with 10,000 periods of consumption inequality, tax-to-output ratio, bank leverage and net worth for autarky and CBDC regime. Simulations are subject to TFP, monetary, cost-push and preference shocks in baseline calibration.

deposits, which are a first-best transaction and savings device. Second, banked households experience net welfare losses due to the tax redistribution effects associated with issuing a CBDC.

Figure 3 illustrates these effects by simulating the model economy with both CBDC and no-CBDC (autarky) regimes, assuming a banked share of $\Gamma_h = 0.75$. In the top panel, we plot the distribution of consumption inequality and the tax-to-output ratio. As a CBDC is introduced, we observe a decline in consumption inequality, which we interpret as an increase in the relative consumption of unbanked households. The introduction of CBDC also leads to an increase in lump-sum taxes levied equally on both households, evidenced by the rightward shift in the distribution of the tax-to-output ratio. The increased tax burden on banked households, combined with the fact that bank deposits are close substitutes for CBDCs, results in negative net welfare effects for banked households.

It is important to note that the welfare effects are not driven by disintermediation. The simulations in Figure 3 show that bank leverage and net worth remain similar in both the CBDC and no-CBDC regimes. Therefore, the tax redistribution mechanism plays a quantitatively more significant role in explaining the welfare effects observed in our model.

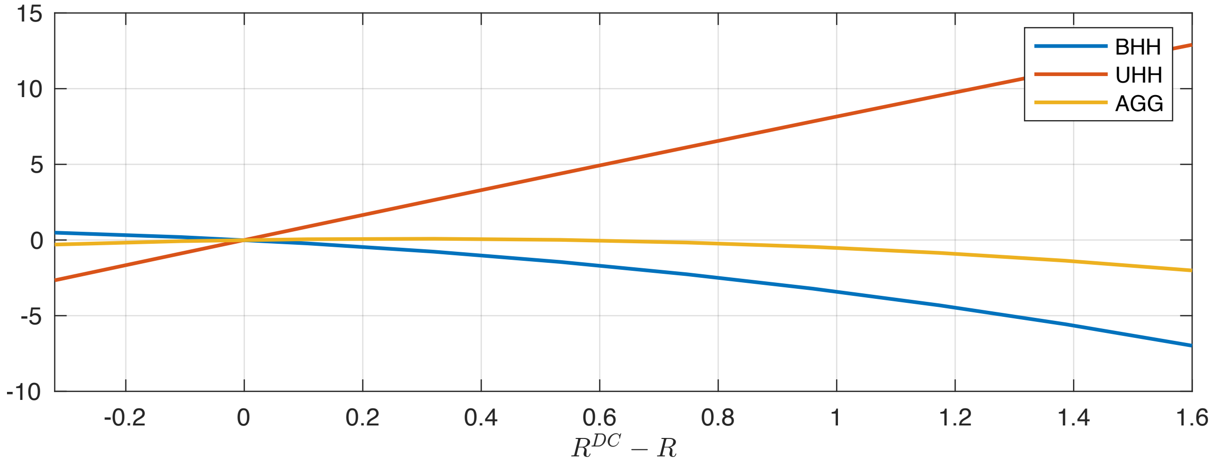
### 3.2.2 Constant Spread Rules

To further illustrate the savings and tax redistribution channels of welfare, we analyse the effects of varying CBDC interest rates, measured by the spread $R_t^{DC} - R_t$. We keep the baseline level of financial inclusion constant ($\Gamma_h = 0.75$) and consider an economy subject to TFP, cost-push, and preference shocks, with monetary policy governed by the Taylor rule. Figure 4 illustrates the relative welfare gains and losses for agents in a CBDC-equipped economy compared to a benchmark scenario where the CBDC rate equals the policy rate ($R_t^{DC} = R_t$). The spread is shown in annualised percentage terms.

Our findings indicate that unbanked households benefit more when CBDC rates exceed the policy rate. This aligns with the savings channel, where higher CBDC interest rates provide unbanked households with a buffer against adverse shocks. On the other hand, banked households experience welfare losses when CBDC rates are higher than the policy rate due to the tax redistribution effect. As CBDC rates rise, both groups shift toward holding more CBDC, funded by increased lump-sum taxes imposed on all households. For banked households, the costs of tax redistribution outweigh the benefits of holding digital currency.

In summary, the optimal spread between the CBDC rate and the policy rate depends on the level of financial inclusion. Our model suggests that in economies with lower financial inclusion and a larger unbanked population, a higher spread between the CBDC rate and the policy rate is preferable. Conversely, in developed economies with a predominantly banked population, the CBDC rate should ideally be set lower than the policy rate. This is consistent with pilot studies in advanced economies with high finan-

Figure 4: **CBDC economy welfare comparison** (% ch.)




Note: Figure plots relative welfare gains for BHH, UHH, and aggregate households as a function of the spread between the policy rate and the CBDC rate. Note that $\Gamma_h = 0.75$.

cial inclusion, such as Sweden's E-Krona, which often propose a non-interest-bearing digital currency.

## 3.3 Optimal Monetary Policy with CBDCs

We now explore the implications for optimal policy, assuming that a policymaker has access to two instruments in order to maximise welfare: nominal interest rates on deposits, $R$, and nominal interest rates on the CBDC, $R^{DC}$. More formally, let us state the problem for the welfare maximising policymaker as:

$$\max_{\{R_{t+s}, R^{DC}_{t+s}\}_{s=0}^{\infty}} \mathbb{V}_t = \Gamma_h \mathbb{V}_t^h + \Gamma_u \mathbb{V}_t^u, \tag{39}$$

subject to the entire set of structural equations as set out in Section 2. As CBDC and deposits are imperfect substitutes, the instruments available to the policymaker are not collinear, allowing us to conduct the optimal policy exercise.[11]

### 3.3.1 Steady state analysis

The steady-state values implied by the solution to the social planner's problem are shown in Figure 5. The choice of instruments by the Ramsey policymaker leads to

11. We argue that $R^{DC}$ is different to $R$ as a Ramsey-instrument in two distinct ways. First, $DC$ is a sub-optimal consumption smoothing instrument to $D$ due to the presence of convex adjustment costs. Secondly, $R^{DC}$ can be set to address consumption inequality and alleviate the CIA constraint of the unbanked, whereas deposit rates cannot be used to address the welfare of the unbanked.

a steady state that generally differs from the one under the baseline configuration with a Taylor rule. The presence of unbanked HH subject to a CIA constraint prompts the social planner to select a deflationary steady state. This result is well-documented in the literature, as seen in works by Chari, Christiano, and Kehoe (1991) and Schmitt-Grohé and Uribe (2010). However, since deflation incurs costs through inefficient price adjustments, the policymaker opts for a relatively low level of deflation.

As the share of unbanked HHs converges to zero ($\Gamma_h \to 1$), indicating greater financial inclusion, the model approaches a standard representative agent setup, and the optimal net inflation rate converges to zero, $\pi \to 1$. Furthermore, when financial inclusion is relatively low ex-ante, the social planner selects higher steady-state CBDC holdings by choosing a larger spread between $R^{DC}$ and $R$. This occurs because, in maximising the aggregate welfare of the economy as expressed in (39), the social planner aims to redistribute resources from the wealthier banked HH to the unbanked HH, which can be achieved only through interest-bearing CBDC holdings.

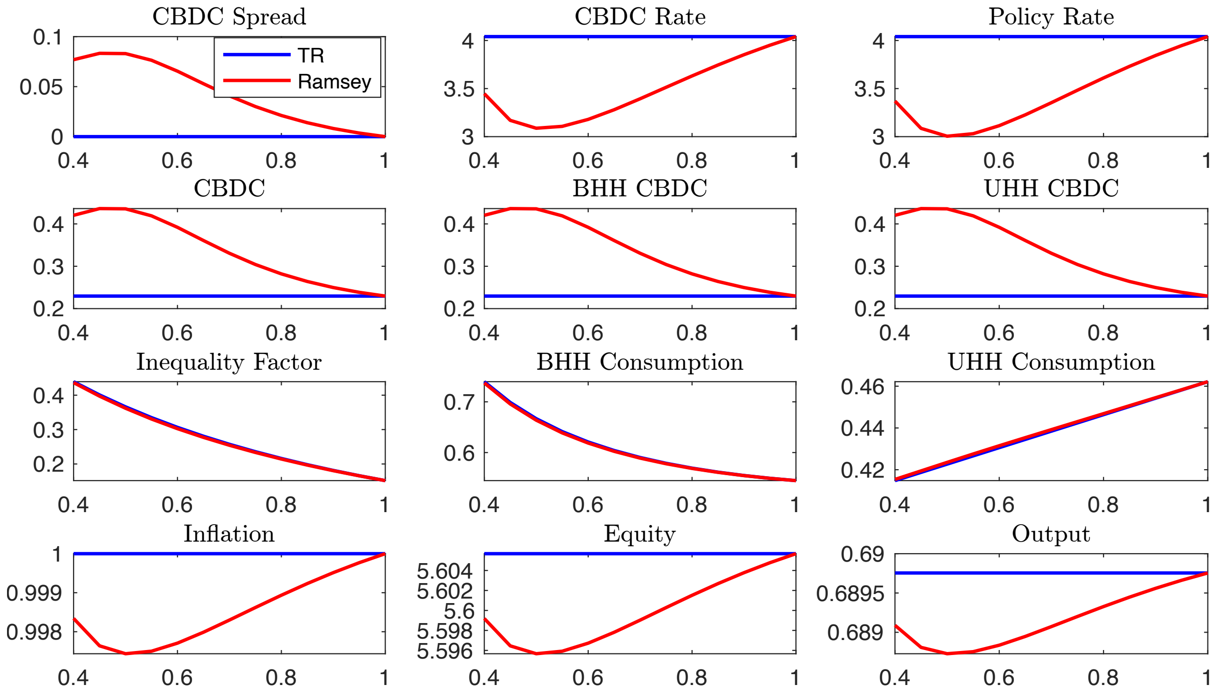
#### 3.3.2 Welfare decomposition: Optimal policy and CBDC introduction

The prior welfare exercises in section 3.2 conducted monetary policy with a Taylor rule. Figure 6 shows the decomposition of welfare gains associated with both the introduction of the CBDC and optimal monetary policy. For different levels of the banked population share, we decompose welfare improvements associated with the transition from the no-CBDC economy and a standard Taylor rule, to the CBDC-equipped economy and a Ramsey-optimal monetary policy (two instruments). The model economy is subject to TFP, markup and preference shocks. These welfare gains are associated with: (i) the introduction of CBDCs, (ii) optimal conventional monetary policy, and (iii) optimal $R_t^{DC}$ setting.[12]

We observe that in economies with low financial inclusion, welfare improvements are primarily driven by the introduction of a CBDC. This aligns with our earlier find-

12. We compare welfare under the three policy changes to the baseline Taylor-rule regime and no CBDCs. The welfare improvements associated with each regime change do not include cross effects, which are small in magnitude. We approximate all the models around the Ramsey-optimal steady state to ensure that welfare rankings are not spurious, following Benigno and Woodford (2012). This implies steady-state deflation and a spread between $R^{DC}$ and $R$.

Figure 5: **Steady state values and financial inclusion**



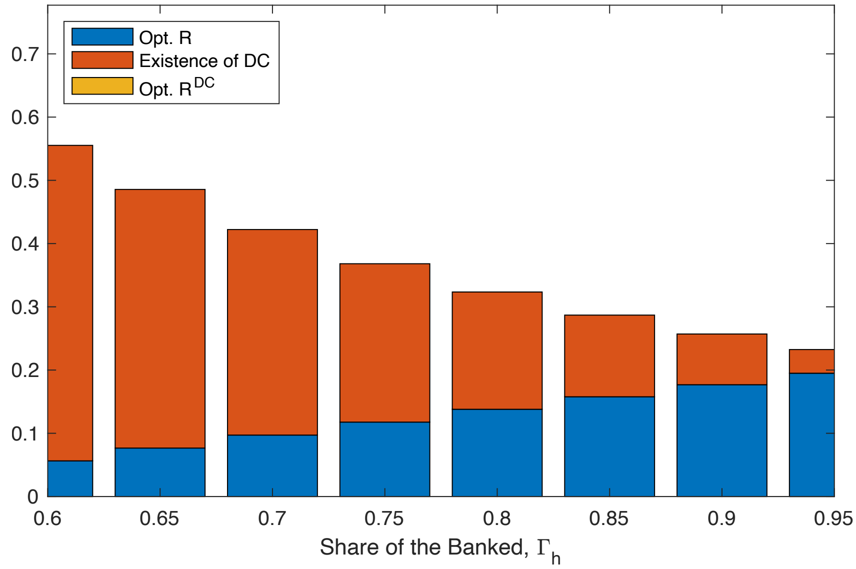

Note: Vertical axis indicates absolute values of variables in steady state, except for $\pi$, $R$, and $R^{DC}$: these variables are represented as annualised rates. The horizontal axes are values of financial inclusion parameter $\Gamma_h$.

ings that a larger unbanked population enhances welfare gains by utilising CBDC as a savings tool.

In contrast, for economies with higher financial inclusion (as $\Gamma_h$ increases), welfare improvements are mainly due to optimal monetary policy, where the CBDC interest rate closely tracks the policy rate. This is intuitive, as a higher share of banked households increases the role of monetary transmission by influencing capital and production through bank balance sheets, utilising a financial accelerator mechanism. The increased importance of monetary policy to stabilise macroeconomic fluctuations increases the gains from conducting optimal monetary policy relative to a benchmark Taylor rule.

When evaluating optimal policy design, we find negligible welfare differences between a single-instrument policy (where the CBDC rate tracks the policy rate, $R^{DC} = R$) and a two-instrument policy (where the CBDC and policy rates are set independently). Although the optimal spread is typically non-zero, as shown in Figure 5, the

Figure 6: **Welfare improvement decomposition**




Note: Vertical axis indicates percent increase in welfare compared to baseline specification without digital currency access.

welfare gains are quantitatively similar to those under a rule where the CBDC rate mirrors the policy rate.

In summary, the welfare gains from introducing a CBDC diminish as financial inclusion increases. An optimal monetary policy, where the CBDC rate closely tracks the policy rate, yields welfare outcomes comparable to those achieved with two instruments. This suggests that deviating from the single-instrument approach, where the CBDC rate tracks the policy rate, offers negligible welfare improvements, with any differences falling within the margin of numerical approximation error.

# 4 Conclusion

This paper analyses the implications of introducing an interest-bearing central bank digital currency (CBDC) on the transmission of monetary policy, distributional and welfare effects, and optimal conduct of monetary policy.

First, the introduction of a CBDC enhances monetary policy transmission by providing unbanked households with an interest-bearing savings tool, improving their ability to smooth consumption in response to shocks. However, this also increases the persistence of monetary shocks on bank equity and net worth, revealing a trade-off between macroeconomic stability and financial stability.

Second, our findings show that higher CBDC rates benefit unbanked households through a savings channel, but they reduce welfare for banked households due to tax redistribution effects. Our findings highlight how the design of the rate of remuneration of the CBDC can be tailored to an economy's financial inclusion level.

Third, our Ramsey optimal policy exercise points to maintaining a constant spread between the CBDC rate and the policy rate. In economies with lower financial inclusion, the primary welfare gains come from introducing a CBDC, while in economies with high financial inclusion, optimal monetary policy becomes the key driver of welfare.

Our paper adds to the ongoing literature on the macroeconomic effects of CBDC issuance. Looking forward, our model could be extended to explore financial stability implications by incorporating occasionally binding constraints and assessing the impact of CBDC introduction on disintermediation during periods of financial stress.

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# A Appendix

## A.1 TANK model with Central Bank Digital Currency

### A.1.1 Final Good Firms

There is a representative competitive final good producing firm which aggregates a continuum of differentiated intermediate inputs according to a Dixit-Stiglitz aggregator:

$$Y_t = \left( \int_0^1 Y_t(i)^{\frac{\epsilon-1}{\epsilon}} di \right)^{\frac{\epsilon}{\epsilon-1}}. \tag{40}$$

Final good firms maximise their profits by selecting how much of each intermediate good to purchase, and so their problem is:

$$\max_{Y_t(i)} P_t Y_t - \int_0^1 P_t Y_t(i) di.$$

Solving for the FOC for a typical intermediate good $i$ is:

$$Y_t(i) = \left[ \frac{P_t(i)}{P_t} \right]^{-\epsilon} Y_t. \tag{41}$$

The relative demand for intermediate good $i$ is dependent of $i$'s relative price with $\epsilon$, the price elasticity of demand, and is proportional to aggregate output, $Y_t$.

From Blanchard and Kiyotaki (1987), we can derive a price index for the aggregate economy:

$$P_t Y_t \equiv \int_0^1 P_t(i) Y_t(i) di.$$

Then, plugging in the demand for good $i$ from (41) we have:

$$P_t = \left( \int_0^1 P_t(i)^{1-\epsilon} di \right)^{\frac{1}{1-\epsilon}}.$$

### A.1.2 Household Optimisation Problem

The FOCs to the BHH problem are:

$$\lambda_t^h = \frac{1}{C_t^h - \zeta_0^h \frac{(L_t^h)^{1+\zeta}}{1+\zeta}}, \tag{42}$$

$$w_t = \zeta_0^h (L_t^h)^{\zeta}, \tag{43}$$

$$1 = \mathbb{E}_t \Lambda_{t,t+1}^h \frac{R_t}{\pi_{t+1}}, \tag{44}$$

$$1 = \mathbb{E}_t \Lambda_{t,t+1}^h \left( \frac{z_{t+1}^k + (1-\delta) Q_{t+1}}{Q_t + \varkappa^h \Gamma_h \left( \frac{K_t^h}{K_t} \right)} \right), \tag{45}$$

$$1 + \varkappa^{DC} \frac{DC_t^h}{\widetilde{DC}^h} = \mathbb{E}_t \Lambda_{t,t+1}^h \frac{R_t^{DC}}{\pi_{t+1}}. \tag{46}$$

The FOCs to the UHH problem are:

$$\lambda_t^u + \alpha_M \mu_t^u = \frac{1}{C_t^u - \zeta_0^u \frac{(L_t^u)^{1+\zeta}}{1+\zeta}}, \tag{47}$$

$$\lambda_t^u w_t = \frac{\zeta_0^u}{C_t^u - \zeta_0^u \frac{(L_t^u)^{1+\zeta}}{1+\zeta}} (L_t^u)^{\zeta}, \tag{48}$$

$$\lambda_t^u \left[1 + \phi_M (M_t - M)\right] = \beta \mathbb{E}_t \xi_{t+1} \left[\frac{\lambda_{t+1}^u + \mu_{t+1}^u}{\pi_{t+1}}\right], \tag{49}$$

$$1 + \varkappa^{DC} \frac{DC_t^u}{\widetilde{DC}^u} = \beta \mathbb{E}_t \xi_{t+1} \frac{\lambda_{t+1}^u}{\lambda_t^u} \frac{R_t^{DC}}{\pi_{t+1}}. \tag{50}$$

### A.1.3 Rewriting the Banker's Problem

To setup the problem of the banker as in Section 2.3, first iterate the banker's flow of funds constraint (13) forward by one period, and then divide through by $n_t$ to yield:

$$\frac{n_{t+1}}{n_t} = \frac{\left(z_{t+1}^k + (1-\delta) Q_{t+1}\right)}{Q_t} \frac{Q_t k_t^b}{n_t} - \frac{R_t}{\pi_{t+1}} \frac{d_t}{n_t}.$$

Rearrange the balance sheet constraint (12) to yield the following:

$$\frac{d_t}{n_t} = \phi_t - 1.$$

Substitute this value for $d_t/n_t$ into the expression for $n_{t+1}/n_t$, and we get:

$$\frac{n_{t+1}}{n_t} = \left(R_{t+1}^k - \frac{R_t}{\pi_{t+1}}\right) \phi_t + \mathbb{E}_t \frac{R_t}{\pi_{t+1}}.$$

Substituting this expression into (16), yields the following:

$$\begin{aligned} \psi_t &= \mathbb{E}_t \Lambda_{t,t+1}^h (1 - \sigma_b + \sigma_b \psi_{t+1}) \left[\left(R_{t+1}^k - \frac{R_t}{\pi_{t+1}}\right) \phi_t + \frac{R_t}{\pi_{t+1}}\right] \\ &= \mu_t \phi_t + \upsilon_t, \end{aligned}$$

which is (18) in the text.

### A.1.4 Solving the Banker's Problem

With $\{\mu_t\} > 0$, the banker's incentive compatibility constraint binds with equality, and so we can write the Lagrangian as:

$$\mathcal{L} = \mu_t \phi_t + \upsilon_t + \lambda_t (\psi_t - \theta^b \phi_t),$$

where $\lambda_t$ is the Lagrangian multiplier. The FOCs are:

$$(1 + \lambda_t) \mu_t = \lambda_t \theta^b, \tag{51}$$

$$\psi_t = \theta^b \phi_t. \tag{52}$$

Substitute (52) into the banker's objective function to yield:

$$\phi_t = \frac{\upsilon_t}{\theta^b - \mu_t}, \tag{53}$$

which is (20) in the text.

### A.1.5 Full Set of Equilibrium Conditions

**Households.**

$$w_t = \zeta_0^h L_t^h \tag{54}$$

$$1 = \mathbb{E}_t \Lambda_{t,t+1}^h \frac{R_t}{\pi_{t+1}} \tag{55}$$

$$1 = \mathbb{E}_t \Lambda_{t,t+1}^h \frac{z_{t+1}^k + (1-\delta) Q_{t+1}}{Q_t + \varkappa^h \Gamma_h \left(\frac{K_t^h}{K_t}\right)} \tag{56}$$

$$1 + \varkappa^{DC} \frac{DC_t^h}{\widetilde{DC}^h} = \mathbb{E}_t \Lambda_{t,t+1}^h \frac{R_t^{DC}}{\pi_{t+1}} \tag{57}$$

$$C_t^u + M_t + \chi_t^M + DC_t^u + \chi_t^{DC,u} + T_t^u = w_t L_t^u + \frac{M_{t-1}}{\pi_t} + \frac{R_{t-1}^{DC}}{\pi_t} DC_{t-1}^u \tag{58}$$

$$\frac{\lambda_t^u}{\lambda_t^u + \alpha_M \mu_t^u} w_t = \zeta_0^u (L_t^u)^\zeta \tag{59}$$

$$\lambda_t^u + \alpha_M \mu_t^u = \frac{1}{C_t^u - \zeta_0^u \frac{(L_t^u)^{1+\zeta}}{1+\zeta}} \tag{60}$$

$$\beta \mathbb{E}_t \xi_{t+1} \frac{\lambda_{t+1}^u + \mu_{t+1}^u}{\pi_{t+1}} = \lambda_t^u \left[1 + \phi_M (M_t - M)\right] \tag{61}$$

$$\lambda_t^u \left(1 + \varkappa^{DC} \frac{DC_t^u}{\widetilde{DC}^u}\right) = \beta \mathbb{E}_t \xi_{t+1} \lambda_{t+1}^u \frac{R_t^{DC}}{\pi_{t+1}} \tag{62}$$

$$\alpha_M C_t^u = \frac{M_{t-1}}{\pi_t} \tag{63}$$

**Production.**

$$Q_t = 1 + \frac{\kappa_I}{2} \left(\frac{I_t}{I} - 1\right)^2 - \frac{I_t}{I} \kappa_I \left(\frac{I_t}{I} - 1\right) \tag{64}$$

$$K_t = (1-\delta) K_{t-1} + I_t \tag{65}$$

$$Y_t = A_t K_{t-1}^\alpha L_t^{1-\alpha} \tag{66}$$

$$\frac{z_t^k K_{t-1}}{w_t L_t} = \frac{\alpha}{1-\alpha} \tag{67}$$

$$MC_t = \frac{1}{A_t} \left(\frac{z_t^k}{\alpha}\right)^\alpha \left(\frac{w_t}{1-\alpha}\right)^{1-\alpha} \tag{68}$$

$$\pi_t(\pi_t - 1) = \frac{\epsilon - 1}{\kappa} \left(\mathcal{M}_t MC_t + \tau - 1\right) + \mathbb{E}_t \Lambda_{t,t+1}^h (\pi_{t+1} - 1) \pi_{t+1} \frac{Y_{t+1}}{Y_t} \tag{69}$$

**Banks.**

$$\psi_t = \theta^b \phi_t \tag{70}$$

$$\phi_t = \frac{v_t}{\theta^b - \mu_t} \tag{71}$$

$$\mu_t = \mathbb{E}_t \Omega_{t,t+1} \left[ \frac{z^k_{t+1} + (1-\delta) Q_{t+1}}{Q_t} - \frac{R_t}{\pi_{t+1}} \right] \tag{72}$$

$$\upsilon_t = \mathbb{E}_t \Omega_{t,t+1} \frac{R_t}{\pi_{t+1}} \tag{73}$$

$$\Omega_{t,t+1} = \Lambda^h_{t,t+1} (1 - \sigma_b + \sigma_b \psi_{t+1}) \tag{74}$$

**Monetary and fiscal policy.**

$$\frac{R_t}{R} = \left( \frac{R_{t-1}}{R} \right)^{\rho_R} \left[ \left( \frac{\pi_t}{\pi} \right)^{\phi_\pi} \left( \frac{Y_t}{Y} \right)^{\phi_Y} \right]^{1-\rho_R} \exp(\varepsilon^R_t) \tag{75}$$

$$\frac{R^{DC}_{t-1}}{\Pi_t} DC_{t-1} + \frac{M_{t-1}}{\Pi_t} = \tau Y_t + \Gamma_h T^h_t + \Gamma_u T^u_t + DC_t + M_t \tag{76}$$

$$R^{DC}_t = R_t \tag{77}$$

**Market clearing.**

$$C_t = \Gamma_h C^h_t + \Gamma_u C^u_t \tag{78}$$

$$L_t = \Gamma_h L^h_t + \Gamma_u L^u_t \tag{79}$$

$$DC_t = \Gamma_h DC^h_t + \Gamma_u DC^u_t \tag{80}$$

$$\omega_t = 1 - \frac{C^u_t}{C^h_t} \tag{81}$$

$$\begin{aligned} Y_t &= C_t + \left[ 1 + \Phi \left( \frac{I_t}{I} \right) \right] I_t + \frac{\kappa}{2} (\pi_t - 1)^2 Y_t \\ &\quad + \Gamma_h (\chi^h_t + \chi^{DC,h}_t) + \Gamma_u (\chi^M_t + \chi^{DC,u}_t) \end{aligned} \tag{82}$$

$$K_t = \Gamma_h (K^h_t + K^b_t) \tag{83}$$

$$\begin{aligned} N_t &= \sigma_b \left[ (z^k_t + (1-\delta) Q_t) K^b_{t-1} - \frac{R_{t-1}}{\pi_t} D_{t-1} \right] \\ &\quad + \gamma_b (z^k_t + (1-\delta) Q_t) \frac{K_{t-1}}{\Gamma_h} \end{aligned} \tag{84}$$

$$Q_t K^b_t = \phi_t N_t \tag{85}$$

$$Q_t K^b_t = D_t + N_t \tag{86}$$

**Exogenous processes.**

$$\ln A_t = \rho_A \ln A_{t-1} + \varepsilon^A_t \tag{87}$$

$$\mathcal{M}_t = (1 - \rho_M) \mathcal{M} + \rho_M \mathcal{M}_{t-1} + \varepsilon^M_t \tag{88}$$

$$\xi_t = \rho_b \xi_{t-1} + \varepsilon^\xi_t \tag{89}$$

### A.1.6 Model Steady State

In the non-stochastic steady state, we have the following:

$$Q = 1,$$

$$\pi = 1,$$
$$R = \frac{1}{\beta},$$
$$R^{DC} = R.$$

We define the discounted spreads on equity as:

$$s = \beta[z^k + (1-\delta)] - 1, \tag{90}$$

which we consider to be endogenous.

From the BHH's FOC with respect to equity, (45), we have:

$$\begin{aligned} 1 &= \beta \left[ \frac{z^k + (1-\delta)}{1 + \varkappa^h \Gamma_h \frac{K^h}{K}} \right] \\ 1 + \varkappa^h \Gamma_h \frac{K^h}{K} &= \beta \left[ z + (1-\delta) \right] \\ \Gamma_h \frac{K^h}{K} &= \frac{s}{\varkappa^h}. \end{aligned} \tag{91}$$

Additionally, in steady state we have:

$$\Omega = \beta(1 - \sigma_b + \sigma_b \psi),$$
$$v = \frac{\Omega}{\beta},$$
$$\mu = \Omega \left[ z^k + (1-\delta) - \frac{1}{\beta} \right],$$

and so, using (90) we can write:

$$\frac{\mu}{v} = s.$$

Next, define $J$ as:

$$J = \frac{n_{t+1}}{n_t} = \left[ z^k + (1-\delta) \right] \frac{K^b}{N} - R \frac{D}{N},$$

and use the following:

$$\frac{D}{N} = \phi - 1,$$
$$\phi = \frac{K^b}{N},$$

to write $J$ as:

$$\begin{aligned} J &= (z^k + (1-\delta) - R)\phi + R \\ &= \frac{1}{\beta} \left[ s\phi + 1 \right]. \end{aligned}$$

Then, from (33) we have:

$$\begin{aligned}
N &= \sigma_b \left\{ \left[z^k + (1-\delta)\right] K^b - RD \right\} + \gamma_b \left[z^k + (1-\delta)\right] \frac{K}{\Gamma} \\
\frac{N}{N} &= \sigma_b \left\{ \left[z^k + (1-\delta)\right] \frac{K^b}{N} - R\frac{D}{N} \right\} + \frac{\gamma_b}{N} \left[z^k + (1-\delta)\right] \frac{K}{\Gamma} \\
\beta &= \sigma_b \beta J + \frac{\gamma_b}{N}\beta \left[z^k + (1-\delta)\right] \frac{K}{\Gamma} \\
&= \sigma_b \beta J + \frac{\gamma_b K^b}{N} \left(1 + \varkappa^h \Gamma \frac{K^h}{K}\right) \frac{K}{\Gamma K^b} \\
&= \sigma_b \beta J + \gamma_b (1+s)\phi \frac{1}{\frac{\Gamma K^b}{K}} \\
&= \sigma_b \beta J + \gamma_b (1+s)\phi \frac{1}{\frac{K - \Gamma K^h}{K}} \\
&= \sigma_b \left[s\phi + 1\right] + \gamma_b (1+s)\phi \frac{1}{1 - \frac{s}{\varkappa^h}} \\
\beta &= \sigma_b + \left[\sigma_b s + \gamma_b \frac{1+s}{1 - \frac{s}{\varkappa^h}}\right] \phi,
\end{aligned}$$

or

$$\phi = \frac{\beta - \sigma_b}{\sigma_b s + \gamma_b \frac{1+s}{1-\frac{s}{\varkappa^h}}}$$

(16) in steady state gives us:

$$\begin{aligned}
\psi &= \beta(1 - \sigma_b + \sigma_b \psi) J \\
&= \beta J - \beta \sigma_b J + \beta \sigma_b \psi J \\
&= \beta(1-\sigma_b) J + \beta \sigma_b \psi J \\
&= \frac{\beta(1-\sigma_b)J}{1 - \beta\sigma_b J} \\
&= \frac{(1-\sigma_b)\left[s\phi + 1\right]}{1 - \sigma_b \left[s\phi + 1\right]} \\
&= \frac{(1-\sigma_b)\left[s\phi + 1\right]}{1 - \sigma_b - \sigma_b s \phi},
\end{aligned}$$

and from (52) we have

$$\psi = \theta^b \phi.$$

Combine the expressions for $\phi$ and $\psi$ to get:

$$\frac{\theta^b(\beta - \sigma_b)}{\sigma_b s + \gamma_b \frac{1+s}{1-\frac{s}{\varkappa^h}}} = \frac{(1-\sigma_b)\left[\frac{s(\beta-\sigma_b)}{\sigma_b s + \gamma_b \frac{1+s}{1-\frac{s}{\varkappa^h}}} + 1\right]}{1 - \sigma_b - \sigma_b \left[\frac{s(\beta-\sigma_b)}{\sigma_b s + \gamma_b \frac{1+s}{1-\frac{s}{\varkappa^h}}}\right]},$$

then rearrange:

$$
\begin{aligned}
H(s) = (1-\sigma_b)\left[s\beta + \gamma_b \frac{1+s}{1-\frac{s}{\varkappa^h}}\right]\left[s\sigma_b + \gamma_b \frac{1+s}{1-\frac{s}{\varkappa^h}}\right] \\
- \theta^b(\beta - \sigma_b)\left[\sigma_b(1-\beta)s + (1-\sigma_b)\gamma_b \frac{1+s}{1-\frac{s}{\varkappa^h}}\right].
\end{aligned}
$$

We can observe that as $\gamma_b \rightarrow 0$,

$$
\begin{aligned}
H(s) &= (1-\sigma_b)s^2\beta\sigma_b - \theta^b(\beta-\sigma_b)\left[\sigma_b(1-\beta)s\right] \\
\implies s &\rightarrow \theta^b \frac{(\beta-\sigma_b)(1-\beta)}{(1-\sigma_b)\beta}.
\end{aligned}
$$

Thus, there exists a unique steady state equilibrium with positive spread $s > 0$ for a small enough $\gamma_b$.

Given $s$, we then yield:

$$
z^k = \frac{1}{\beta}(1+s) - (1-\delta),
$$

and from (3) in the steady state:

$$
MC = \frac{1-\tau}{\mathcal{M}},
$$

and with (67), (2), and (4) we get:

$$
MC = \frac{z^k}{\alpha}\frac{K}{Y},
$$

or

$$
\frac{K}{Y} = MC\frac{\alpha}{z^k}.
$$

From the FOCs of the BHH and UHH problem, we have:

$$
\begin{aligned}
w &= \zeta_0^h (L^h)^\zeta, \\
w &= \frac{\zeta_0^u (L^u)^\zeta (1 + \frac{\alpha_M}{\beta} - \alpha_M)}{\left[C^u - \zeta_0^u \frac{(L^u)^{1+\zeta}}{1+\zeta}\right]}.
\end{aligned}
$$

But since we have that $\zeta_0^u = \frac{\zeta_0^h}{(1+\frac{\alpha_M}{\beta}-\alpha_M)}$, we can write:

$$
w = \zeta_0^h L^\zeta.
$$

We can then use our previous expression for $w$ to express $L$ as a function of $z^k$:

$$
L = \left[\frac{1-\alpha}{\zeta_0^h}\left(\frac{z^k}{\alpha}\right)^{\frac{\alpha}{\alpha-1}}\right]^{\frac{1}{\zeta}}.
$$

Since we know that

$$
w = (1-\alpha)\frac{Y}{L},
$$

we yield:

$$
Y = \frac{\zeta_0^h}{\alpha}\left[\frac{1-\alpha}{\zeta_0^h}\left(\frac{z^k}{\alpha}\right)^{\frac{\alpha}{\alpha-1}}\right]^{\frac{1+\zeta}{\zeta}}.
$$

Additionally, we have:

$$\frac{I}{K} = \delta,$$

and

$$\frac{1}{\beta} = \frac{\alpha \frac{Y}{K} + 1 - \delta}{1 + \varkappa^h \Gamma_h \frac{K^h}{K}}$$

$$\Leftrightarrow \frac{Y}{K} = \frac{\beta^{-1}(1+s) + \delta - 1}{\alpha},$$

from (91), and

$$\frac{I}{Y} = \frac{I/K}{Y/K} = \frac{\alpha\delta}{\beta^{-1}(1+s)+\delta-1}.$$

These of course imply:

$$K = \left[\frac{1-\alpha}{\zeta_0^h}\left(\frac{z^k}{\alpha}\right)^{\frac{\alpha}{\alpha-1}}\right]^{\frac{1+\zeta}{\zeta}} \frac{\zeta_0^h}{\beta^{-1}(1+s)+\delta-1}$$

With $K$ and $s$ in hand, we can then turn back to the BHH's FOC wrt to equity, (45), to find $K^h$:

$$K^h = \frac{s}{\varkappa^h}\frac{K}{\Gamma_h},$$

and also get $K^b$:

$$K^b = \frac{K}{\Gamma_h} - K^h.$$

This then gives us $N$ as we already solved $\phi$:

$$N = \frac{K^b}{\phi}.$$

Then $D$ is also solved as a residual from (12):

$$D = K^b - N.$$

Given $Y$, $I$, and $K$, we can get $C$:

$$\frac{C}{Y} = 1 - \frac{I}{Y} - \frac{\varkappa^h}{2}(\Gamma_h K^h)^2 \left(\frac{K}{Y}\right)^{-1}.$$

From the UHH's FOC with respect to $M$, we have:

$$\mu^u = \lambda^u\left(\frac{1}{\beta} - 1\right),$$

and the FOC with respect to consumption gives us an expression for the marginal utility from consumption:

$$\left(C^u - \zeta_0^u \frac{(L^u)^{1+\zeta}}{1+\zeta}\right)^{-1} = \lambda^u\left(1 + \frac{\alpha_M}{\beta} - \alpha_M\right).$$

Thus, we can express $\lambda^u$ as a function of the marginal utility of consumption:

$$\frac{1}{\lambda^u} = \left(1 + \frac{\alpha_M}{\beta} - \alpha_M\right)\left(C^u - \zeta_0^u \frac{(L^u)^{1+\zeta}}{1+\zeta}\right),$$

noting that because of the values of $\zeta_0^h$ and $\zeta_0^u$, we have:

$$L^u = \left(\frac{w}{\zeta_0^h}\right)^{\frac{1}{\zeta}}.$$

Finally, much like aggregate digital currency holdings, the BHH will not hold any digital currency holdings in steady state due to the presence of management costs. This means that in steady state:

$$DC^h = \frac{\beta R^{DC} - 1}{\varkappa^{DC}} + \widetilde{DC}^h$$

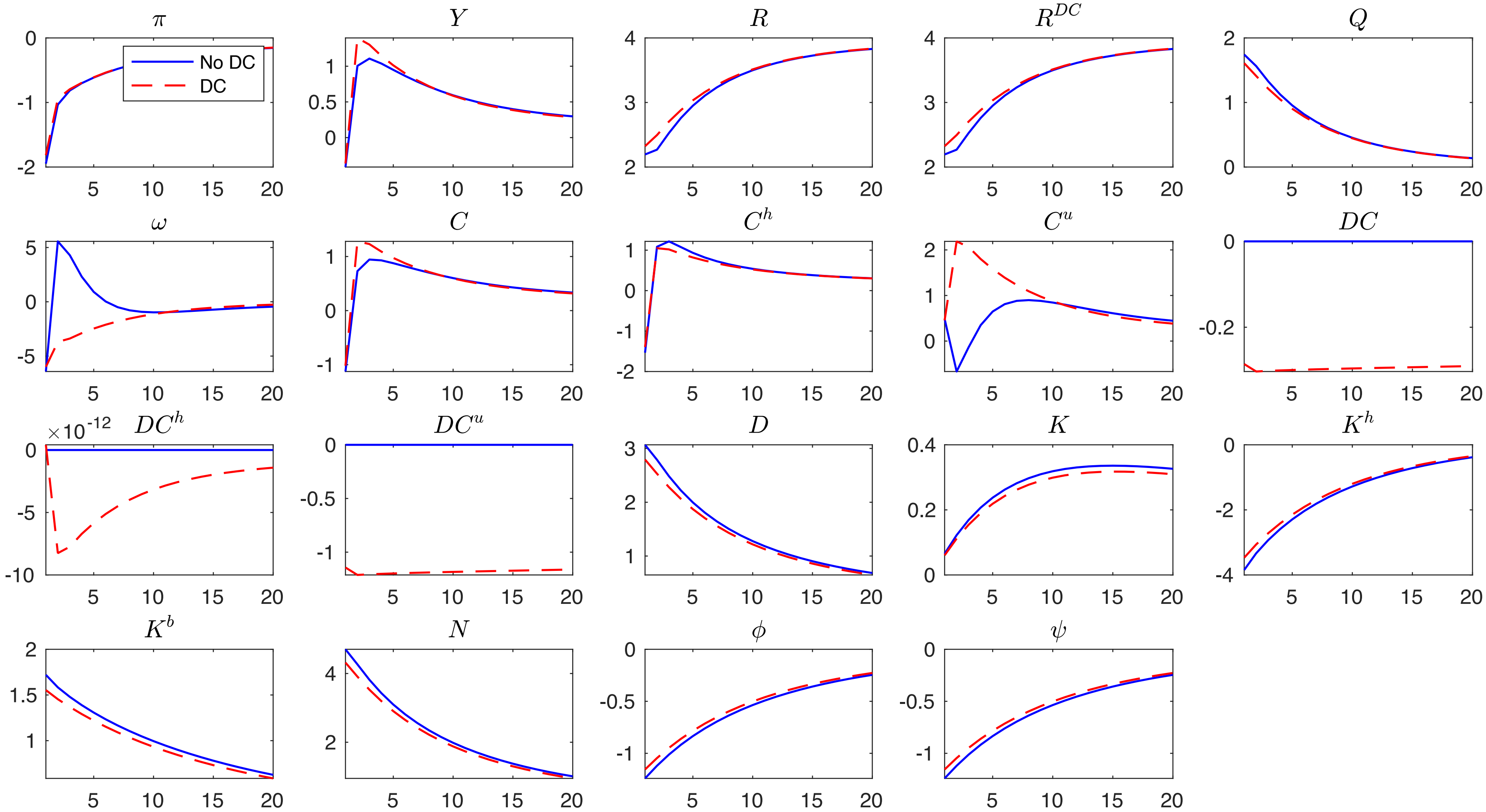
which, of course, implies:

$$DC^u = \frac{\beta R^{DC} - 1}{\varkappa^{DC}} + \widetilde{DC}^u.$$

## A.2 Additional Impulse Responses to Shocks

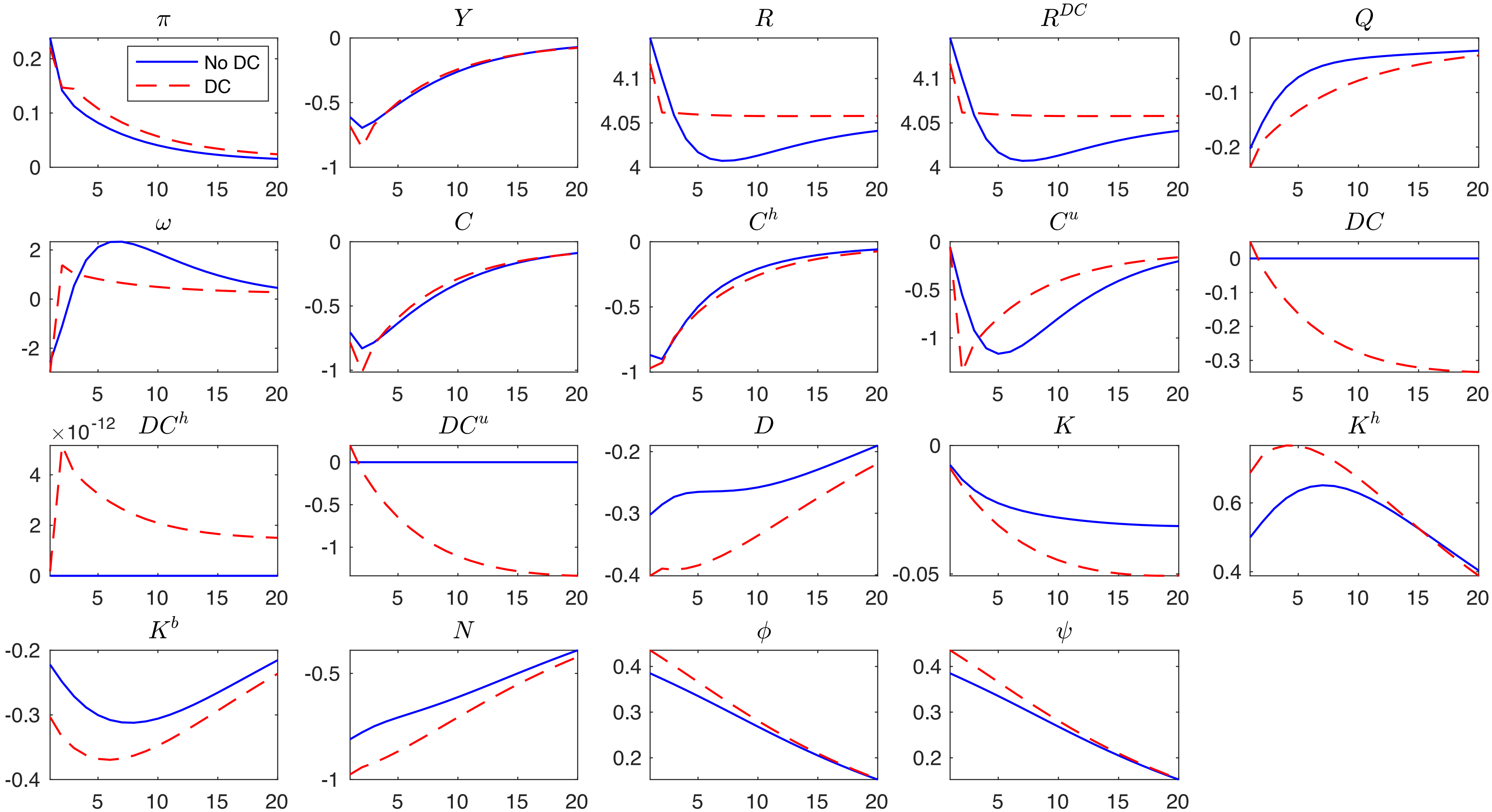
Figures 7, 8, and 9 present results in response to an annualised 1% orthogonal innovation to TFP, cost-push, and preference shocks, respectively. The figures compare IRFs for a no-CBDC economy and to a CBDC-equipped economy.

Figure 7: **IRFs to a 1% TFP shock**



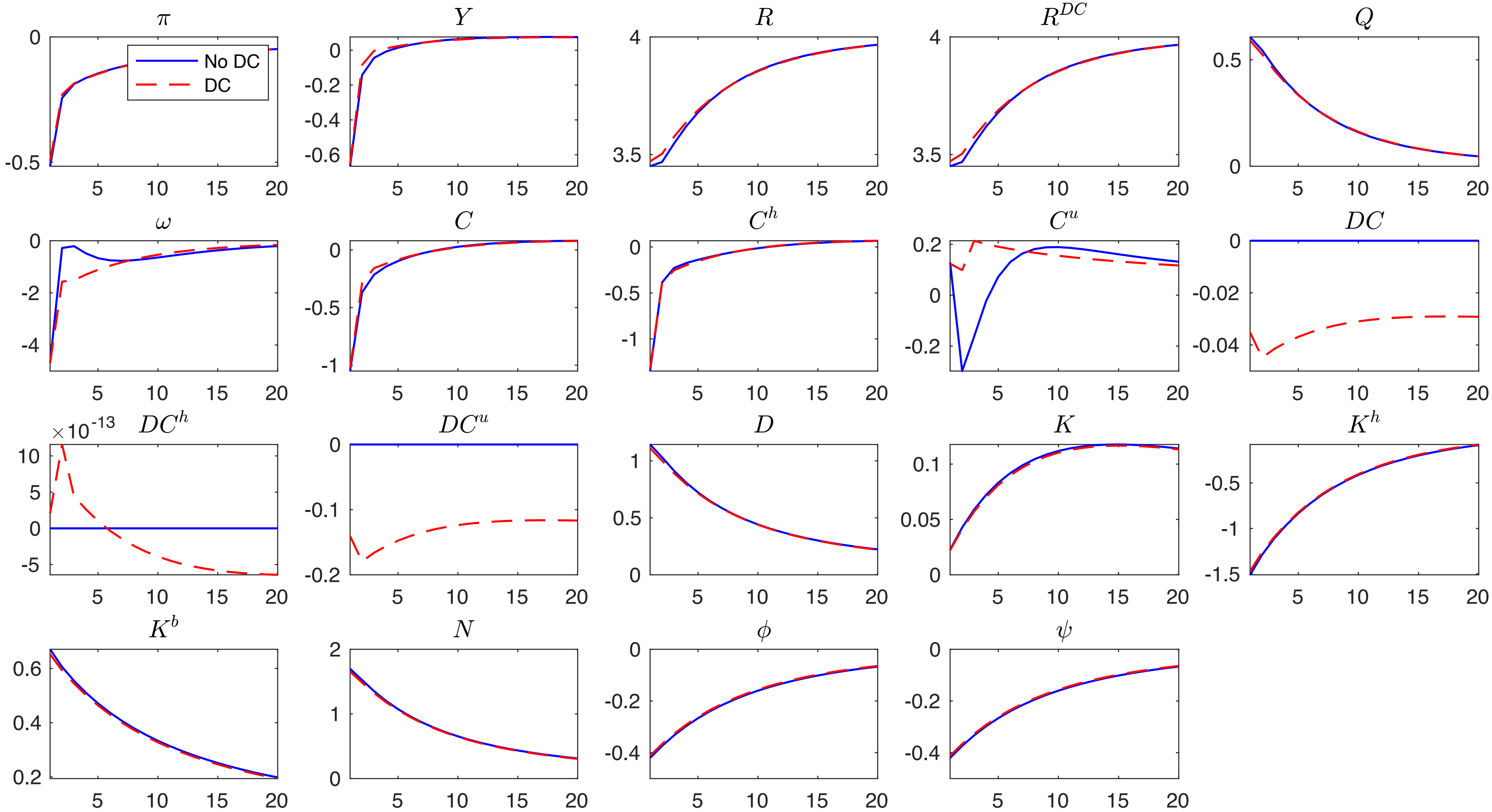

Note: Figure plots impulse responses of model variables with respect to a 1 % annualised innovation to TFP. Time periods are measured in quarters, and responses are measured as a percent deviation from steady state except for Inflation ($\pi$), Nominal Interest Rates ($R$), and Digital Currency Returns ($R^{DC}$) which are expressed as annualised net rates.

Figure 8: **IRFs to a 1% cost-push shock**



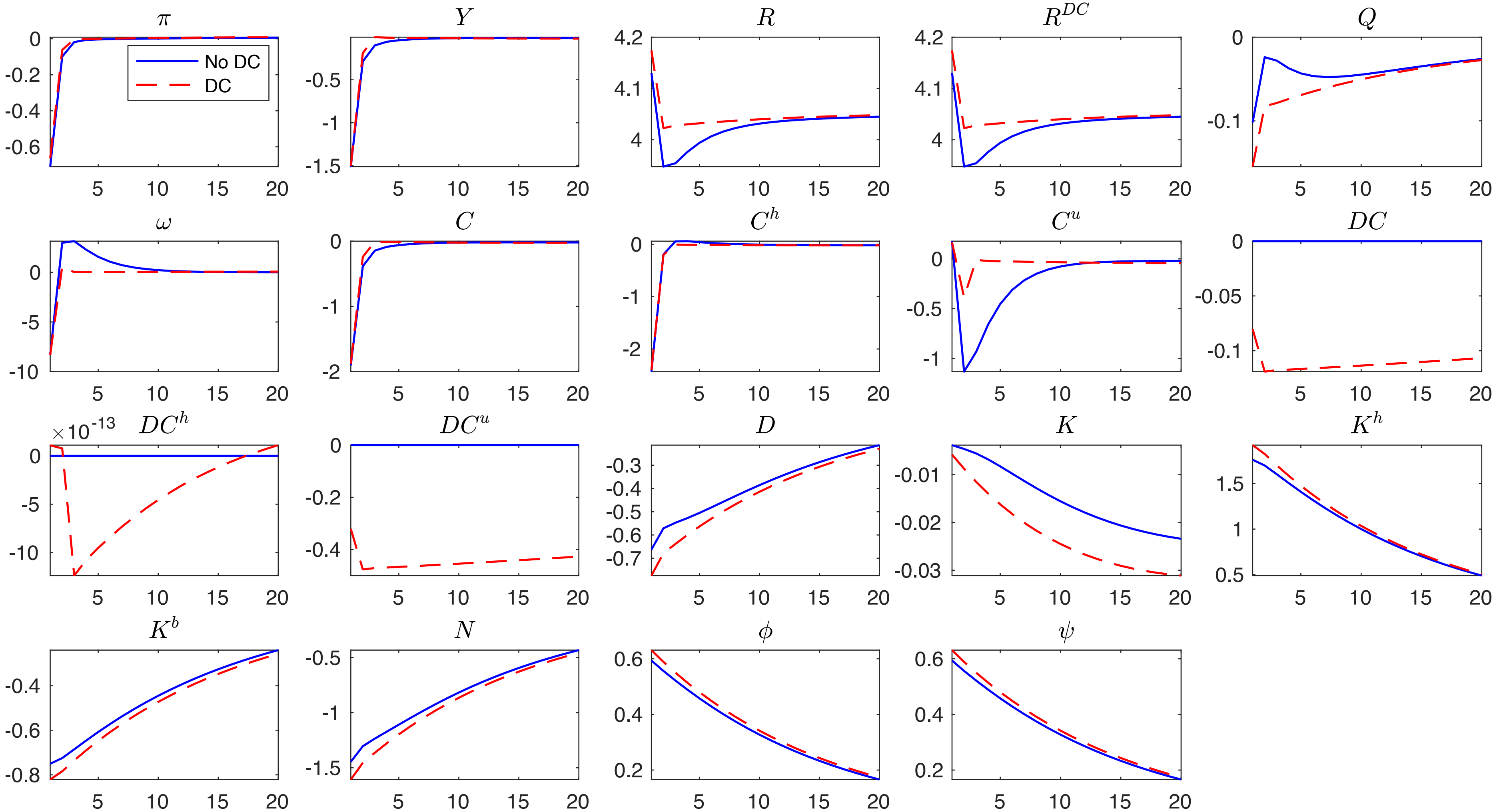

Note: Figure plots impulse responses of model variables with respect to a 1 % annualised innovation to markups. Time periods are measured in quarters, and responses are measured as a percent deviation from steady state except for Inflation ($\pi$), Nominal Interest Rates ($R$), and Digital Currency Returns ($R^{DC}$) which are expressed as annualised net rates.

Figure 9: **IRFs to a 1% demand shock**




Note: Figure plots impulse responses of model variables with respect to a 1% preference shock. Time periods are measured in quarters, and responses are measured as a percent deviation from steady state except for Inflation ($\pi$), Nominal Interest Rates ($R$) and Digital Currency Returns ($R^{DC}$) which are expressed as annualised net rates.

Figure 10: **IRFs to a 1% annualised monetary policy (tightening) shock**




Note: Figure plots impulse responses of model variables with respect to a 1% annualised monetary policy shock. Time periods are measured in quarters, and responses are measured as a percent deviation from steady state except for Inflation ($\pi$), Nominal Interest Rates ($R$) and Digital Currency Returns ($R^{DC}$) which are expressed as annualised net rates.