Policies for Managing Disintermediation with CBDCs

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Abstract

Understanding and testing the proposed design frameworks is crucial as the concept of a Central Bank Digital Currency becomes more popular. The primary concern is the potential for financial disintermediation if agents take their deposits from commercial banks, preferring to hold CBDCs, particularly in times of uncertainty. Three potential solutions have been suggested. The first is a ceiling on CBDC holdings, preventing agents from holding a CBDC above a certain threshold. The second is an adjustable interest rate, and the third is a countercyclical two-tier interest rate, by which a relatively attractive interest rate is paid on CBDC holdings up to a threshold, and a relatively unattractive interest rate is paid above. This paper tests the efficacy and the welfare effects of these policies in a New Keynesian DSGE framework. It finds that all the policies have a disintermediating effect and improve overall welfare compared to a CBDC with no restrictions. The holding ceiling policy has the greatest welfare improvements and antidisintermediating power.

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1 Introduction

With around 80% of central banks exploring the opportunity of developing a CBDC (Bank for International Settlements et al., 2020), the concept of digital, central bank money that can be used to make transactions and as a store of value, and held in an account directly with the central bank has captured the attention of both economists and the public.[1] However, while the CBDC will bring about new benefits both for users and for central banks, the risk of large scale financial intermediations calls into question the most suitable design structure for these unprecedented currencies.

Over recent decades, the current global payment network has been adapted to accommodate the growing demand and modern technical requirements (Bech and Hancock, 2020). CBCDs provide the opportunity to redesign inefficient payment systems and increase access to transaction services while providing monetary authorities with new tools for meeting their monetary and financial stability goals. To maintain financial stability, the resilience of the payments network is crucial. Built from the ground up with modern technologies, a new central bank digital currency could greatly improve this resilience and provide a basis for future developments in the payment network landscape. Further, CBDCs could be used by monetary authorities as an additional channel for monetary policy. As an alternative to bank deposits, an interest-bearing CBDC would allow for the changes in policy rates to transmit more quickly to agents, consequently improving the effectiveness of monetary policy (Meaning et al., 2018).

While a CBDC has many potential benefits, a primary concern is the threat of dis-

[1] For a review of central bank digital currency opportunities and design considerations see Bank of England (2020). See Boar et al. (2020) for a recent survey of the CBDC literature.

intermediation that a CBDC might pose. Disintermediation is the process through which individuals withdraw their deposits from private banks, preferring to hold an alternative asset, in this case, a CBDC. Because of this, lending to firms from private banks, which rely on these deposits to facilitate this lending, is forced to decrease. This decrease in lending can lead to a financial accelerator effect, reducing investment and future output more. Further, this reduction in bank's balance sheets causes more financial stress, thus causing more agents to withdraw their deposits. In this case, the central bank may be forced to step in as a lender of last resort to ensure that commercial banks can maintain their lending levels, leading to an unprecedented increase in central bank balance sheets. This increase in central bank liabilities raises the question of which assets should be used to hold against them; this is particularly important following the large increase in central bank balance sheets following the COVID-19 pandemic (Pierret and Steri, 2018).

With this threat present, many authors have proposed solutions that could go some way to mitigating the disintermediating effect of a CBDC. Kumhof and Noone (2018) provide a framework of four key principles for CBDC design in order to mitigate reductions in commercial bank funding. Additionally, two other structural designs have been proposed. Panetta (2018) suggests a hard ceiling on CBDC holdings; while this is technically plausible, it is likely to add significant inefficiencies both for usage and within the transaction network. Secondly, Bindseil (2020) proposes the idea of a two-tiered interest rate structure. Under this policy, a relatively attractive interest rate is paid on CBDC holdings up to a threshold, and a relatively unattractive interest rate is paid above this threshold. This formulation allows CDBC as a payment method to be unrestricted while discouraging usage of the CBDC as a store of value, consequently mitigating disintermediation.

While these policies have been proposed, with no CBDC currently existing, data and therefore empirical methods are not available. This creates a research challenge when assessing these policies' effectiveness, macroeconomic, and welfare effects. This paper extends a medium-scale DSGE model, occasionally using binding constraints to go some way to answering these questions.[2]

While the problem of disintermediation is well known, and there is a growing mass of literature focused on the impacts of introduction CBDCs, this paper's motivation stem from the distinct gap in the model-based research on the implications and economic effects of the different policies intended to mitigate disintermediation in a CBDC economy.

This paper has three notable contributions. Extending Gross and Schiller (2020), the model presented incorporates three potential methods for mitigating the disintermediating effect that a CBDC causes in response to a negative economic shock.

Firstly, an asset-elastic interest rate, causing the premium between the interest rate on deposits and CBDC to get larger the more CBDC that an agent holds, to increase the equilibrium level of a bank run to CBDC in the event of increased financial stress, is introduced. Using the basis of the debt-elastic interest rate presented in Schmitt-Grohé and Uribe (2003), this provides a continuous, thus tractable method of implementing a Kumhof and Noone (2018) style adjustable interest rate.

Secondly, the paper goes further to introduce a CBDC holding ceiling, as proposed

[2]Simulations are modelled in Dynare. The functionality to simulate models with occasionally binding constraints implement the MatLab/Dynare toolkit provided by Guerrieri and Iacoviello (2015).

by Panetta (2018). While this method of mitigating the risk of large scale disintermediation is more realistic, it provides challenges for incorporation into a DSGE model because of the non-linearities introduced. This paper uses the 'OccBin' package created by Guerrieri and Iacoviello (2015) to approximate the occasionally binding constraint that this specification induces, thus circumventing the problem.

Finally, the paper provides a model for a two-tiered interest rate structure. This structure introduces a countercyclical penalty for holding CBDC above a given threshold, thus making it costly for households to hold CBDC in an economic downturn.

The paper finds that, while all of the CBDC policies significantly reduce the peak levels of CBDC holdings, the holding ceiling policy has the greatest antidisintermediation effect, showing a 4.2 percentage point difference in disintermediation compared to the baseline of a CBDC with no restrictions. The elastic-interest rate model reduces disintermediation by 3.7 percentage points, and the two-tier model generates an antidisintermediation effect of 2.2 percentage points. The welfare results are similar; the holding-ceiling policy generates an 8.58% welfare improvement compared to the baseline CBDC model, and the two-tier model generates a 3.99% welfare improvement.

The paper is structured as follows, section 2 provides an overview of the current DSGE research on the macroeconomic effects of CBDCs, current work on disintermediation and the proposed policies to mitigate disintermediation effects. Section 3 details the model used in the paper and provides the functional forms for the various interest rate structures. Finally, section 4 presents the impulse response functions for the models, an analysis of the policy welfare effects, and a comparison of the proposed structures both in their antidisintermediating effect and design implications. The paper finds that, while all of the CBDC policies significantly reduce the peak levels of CBDC holdings, the holding ceiling policy has the greatest antidisintermediation effect, showing a 4.2 percentage point difference in disintermediation compared to the baseline of a CBDC with no restrictions. The elastic-interest rate model reduces disintermediation by 3.7 percentage points, and the two-tier model generates an antidisintermediation effect of 2.2 percentage points. The welfare results are similar; the holding-ceiling policy generates an 8.58% welfare improvement compared to the baseline CBDC model, and the two-tier model generates a 3.99% welfare improvement.

2 Literature Review

While much of the work on Central Bank Digital Currencies has been qualitative, there is flourishing literature integrating CBDCs into DSGE models. Barrdear and Kumhof (2021a) presents a model calibrated with US data over the period 1990-2006 in order to assess the macroeconomic effects associated with the introduction of a CBDC. The paper finds that CBDCs bring about several macroeconomic benefits, including a 3% increase in steady-state output.

The problem of disintermediation following the introduction of a CBDC has been a focus in recent times, Bitter (2020) studies the effects of a banking crisis in the presence of a CBDC, extending Gertler and Kiyotaki (2015). In contradiction to Barrdear and Kumhof (2021a), this work finds that the introduction of a CBDC does not affect aggregate output or prices; however, it materially affects the constitution of household savings, bank funding and capital investment - leading to a reduction in bank profits. Further, the paper finds that CBDCs stabilise the economy in times of crisis by deferring bank-run equilibrium to larger shocks. Bindseil (2020) reinstates this, stating that large scale transfers from household bank deposits to CBDC could lead to significant financial disintermediation.

Mersch (2018) emphasises the potential for destabilising effects of CBDCs after a financial crisis. Specifically, the increase in demand for CBDCs as a 'risk-free' asset during a period of uncertainty could impose a destabilisation effect on commercial bank deposits, increasing volatility (Armelius et al., 2018; Camera, 2016). Nevertheless, a study conducted by Mancini-Griffoli et al. (2018) disputes the negative effect of CBDCs in a crisis, concluding that any overall effects are likely to be dampened, Juks (2018) draws similar conclusions.

Gross and Schiller (2020) explores the disintermediating effects of CBDCs in a DSGE model, comparing the effects of CBDCs that are interest-bearing and those that are not. Extending Gertler and Karadi (2011), this research finds that in a 'full allotment' for external refinancing scenario where the central bank will fully compensate for the fall in private deposits, CBDCs bring about stability in the financial sector. However, this is through the mechanism of shifting external refinancing from household deposits to central bank funding. This heavier reliance on the central bank also reduces the likelihood of bank runs at the cost of a substantial increase in the central bank balance sheet.

Having examined the disintermediating effects of introducing a CBDC, a natural question asks what the first-best solution that allows the benefits of the CBDC but mitigates the losses in bank deposits is. Several potential solutions have been considered. Kumhof and Noone (2018) proposes four principles for designing a CBDC. The first is a variable rate interest rate on CBDCs, emphasised i) to avoid the depreciation of CBDCs relative to other forms of money or a breakdown of parity and ii) if a general price level clears the market, this will reduce the real value of nominal CBDC balances; both of which are highly undesirable for central banks. The second key principle is that CBDC and conventional central bank reserves are distinct and not convertible, allowing central banks to employ CBDC as an additional policy instrument. Thirdly, there is no guaranteed or on-demand convertibility of bank deposits into CBDC at commercial banks. Finally, the central bank issues CBDC only against eligible government securities, allowing central banks to manage their own risk. Kumhof and Noone (2018) find that these design principles mostly eliminate the risk of an aggregate run of the banking sector.

Panetta (2018) discusses the opportunity to impose an upper bound on CBDC holdings.[3] While this policy would be plausible in terms of technological implementation, several economic implications make the policy undesirable. Implementing a ceiling on CBDC holdings would require checking transactions to ensure that the recipient will not be taken above the ceiling before execution. This would introduce major frictions, thus undermining the resilience of the payment system (Bindseil, 2020).

Bindseil (2020) proposes a two-tiered interest rate system has been proposed by Bindseil (2020); in this scenario, a relatively attractive interest rate is paid on CBDC

[3]While Panetta (2018) discusses the holding ceiling policy, he also goes on to discuss the possibility of the tiered interest scheme. However, in this paper, for ease of disambiguation, we attribute Bindseil (2020) to the two-tier structure due to the more in-depth treatment of the policy.

holdings up to a ceiling, after which a lower interest rate is applied. Up to the point of the threshold, agents would never face negative interest rates; to ensure that CBDC remains attractive to households. However, beyond the threshold, the remuneration would be low such that CBDC holdings are solely beneficial when making large one-off payments and not a sustained form of investment.

The central question of this paper asks what the implications of the alternative interest rate policies are. Barrdear and Kumhof (2021a) analyses the effects of interest-rate based rules compared to allocation based rules and countercyclical policies. The work finds that a countercyclical interest rate rule can significantly help stabilise business cycle dynamics. Further, they find that with lower substitutability between CBDCs and deposits, interest rate rules require more aggressive calibration in order to deliver the same countercyclical effects compared to the quantity limits.

3 Model

This paper extends the New Keynesian model with financial intermediaries created by Gertler and Karadi (2011). Commercial banks are introduced through a fixed proportion of households that act as bankers, taking household deposits and central bank funds, intermediating them to intermediate goods producers. As in Gertler and Karadi (2011), there is a mechanism for bank defaults, enforcing an endogenous ceiling on commercial bank's balance sheets, causing a moral hazard and a financial accelerator effect.

The canonical model is extended by introducing CBDCs, using the specification from Gross and Schiller (2020), including CBDCs in the objective function of the household, using a money-in-utility specification (Sidrauski, 1967). In the baseline model, the interest rate on CBDC is set as a fixed spread from the Central Bank's policy rate, i^{CB}.

Finally, this paper proposes three further extensions. The first is an asset-elastic interest rate which endogenously alters the spread between deposits and CBDC, making the CBDC relatively less attractive the more CBDC households hold. The second is a fixed ceiling on CBDC holdings, proposed by Panetta (2018) and finally, the third is a countercyclical two-tier interest rate system, proposed by Bindseil (2020), that penalises CBDC holdings above a certain threshold, depending on the level of stress in the financial sector.

3.1 Households

There is a continuum of households that consume goods, supply labour and save. There are three instruments for savings, government bonds, B, bank deposits, D, or the Central Bank Digital Currency (CBDC), $CBDC$. Denoting the real interest rates on government bonds to be r^B, commercial bank deposits as r^D and CBDC as r^{CBDC}, we assume that there is an initial premium between deposits, CBDC and bonds such that $r^B > r^D > r^{\text{CBDC}}$.

The representative household's problem can be written:

$$\max E_t \sum_{i=0}^{\infty} \beta^i \left\{ \ln\left(C_{t+i} - hC_{t+i-1}\right) + \frac{\Upsilon}{1+\Gamma}\left(D_{t+i} + CBDC_{t+i}\right)^{1+\Gamma} - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \right\} \tag{1}$$

where C_t is consumption and L_t is labour supply. Υ represents the relative utility weights between real balances, CBDC and deposits, and χ is the relative weight of labour. The parameter Γ is the elasticity of money balances, and ϕ is the Frisch elasticity of the labour supply. As in Gertler and Karadi (2011), h acts as a habit formation parameter on consumption.

The household optimises this objective function subject to its budget constraint:

$$C_t+D_t+CBDC_t+B_t = w_tL_t+F_t+\left(1+r^D_{t-1}\right)\psi_{t-1}D_{t-1}+\left(1+r^{CBDC}_{t-1}\right)CBDC_{t-1}+\left(1+r^B_{t-1}\right)B_{t-1} \tag{2}$$

where w_t is the real wage and F_t represents lump-sum transfers from the ownership of non-financial and financial firms.

In making the decision on the allocation of bank deposits, households make a judgement of the bank's risk of default, incorporating this risk into the deposit discount factor, ψ_t, this risk is specified by:

$$\psi_t = 1-\left(\frac{D_t}{F^*_t}\right)^{\Omega_D} - \frac{\bar{N}-N_t}{\bar{N}}\Omega_N \tag{3}$$

The discount rate is increasing in deposits and decreasing in the level of stress in the financial sector. F^* is the maximum amount of external refinancing from deposits and central bank funds, $\bar{N}$ is the steady-state level of banks net worth, and N_t is the net worth of banks at time t. The parameters Ω_D and Ω_N represents the steady-state ratio of deposits to central bank funds (Gross and Schiller, 2020) and the weight of changes in banks equity N on ϕ.[4]

[4]This specification abstracts from deposit insurance schemes, see Gross and Schiller (2020).

3.2 Banks

Banks intermediate their equity, the deposits from households and central bank funds R^{CB} to the production sector. They pay bank household deposits and central bank funds with the *ex ante* real interest rates, which are set by the monetary authority. Borrowers (intermediate goods producers) transfer profits to banks; this is captured in the interest rate on capital, r^k.

Over their lifetime, a banker j builds wealth N_j. This wealth represents the assets of the bank, while deposits and central bank funds constitute liabilities. From this, the balance sheet of bank j is:

$$Q_t S_{jt} + N_{jt} + D_{jt} + R_{jt}^{CB} \tag{4}$$

where S_j are financial claims, priced at Q, in the production sector.

The capital of banks is driven through the interest spreads between what is paid (on deposits and central bank funding) and received on loans, $r_{t+1}^K - r_t^D$ and $r_{t+1}^K - r_t^{CB}$. As long as these premia are positive, a bank can continue to intermediate funds.

Banks maximise their expected terminal wealth:

$$V_{jt} = E_t \sum_{i=0}^{\infty} (1-\theta)\theta^i \beta^{i+1} \Lambda_{t,t+i+1} \left(N_{jt+i+1}\right) \tag{5}$$

where θ is the probability that the bank stays in operation in the next period. This terminal wealth can be expressed recursively as:

$$V_{jt} = mu_t^N N_{jt} + mu_t^D D_{jt} + mu_t^R R_{jt}^{CB} \tag{6}$$

where mu represents the marginal utility of alternative sources of funding:

$$mu_t^N = E_t \left[(1-\theta)\beta\Lambda_{t,t+1} \left(1 + r_{t+1}^K\right) + \beta\Lambda_{t,t+1}\theta\Delta_{t,t+1}^N mu_{t+1}^N \right] \tag{7}$$

$$mu_t^D = E_t \left[(1-\theta)\beta\Lambda_{t,t+1} \left(r_{t+1}^K - r_t^D\right) + \beta\Lambda_{t,t+1}\theta\Delta_{t,t+1}^D mu_{t+1}^D \right] \tag{8}$$

$$mu_t^R = E_t \left[(1-\theta)\beta\Lambda_{t,t+1} \left(r_{t+1}^K - r_t^{CB}\right) + \beta\Lambda_{t,t+1}\theta\Delta_{t,t+1}^R mu_{t+1}^R \right] \tag{9}$$

These expressions include $\Delta_{t,t+1}^N$, $\Delta_{t,t+1}^D$ and $\Delta_{t,t+1}^R$, which are the growth rates of equity, deposits and central bank funding respectively. These growth rates can be written:

$$\Delta_{t,t+1}^N = \frac{N_{jt+1}}{N_{jt}} = \left(1 + r_{t+1}^K\right) + \left(r_{t+1}^k - r_t^D\right)\frac{D_t}{N_t} + \left(r_{t+1}^k - r_t^{CB}\right)\frac{R_t^{CB}}{N_t} \tag{10}$$

$$\Delta_{t,t+1}^D = \frac{D_{jt+1}}{D_{jt}} = \frac{D_{t+1}}{D_t}\Delta_{t,t+1}^N \frac{N_t}{N_{t+1}} \tag{11}$$

$$\Delta_{t,t+1}^R = \frac{R_{jt+1}^{CB}}{R_{jt}^{CB}} = \frac{R_{t+1}^{CB}}{R_t^{CB}}\Delta_{t,t+1}^N \frac{N_t}{N_{t+1}} \tag{12}$$

The bank faces an incentive constraint. A banker j can choose to exit the market if the income generated from intermediating funds exceeds their expected terminal wealth. Thus, this constraint can be written:

$$V_{jt} \geq \lambda Q_t S_{jt} \tag{13}$$

Combining these, this constraint can be written:

$$mu_t^N N_{jt} + mu_t^D D_{jt} + mu_t^R R_{jt}^{CB} \geq \lambda Q_t S_{jt} \tag{14}$$

Assuming this constraint is binding, and totalling over all banks, we can derive an expression for the total external refinancing of banks, F_t^*:

$$F_t^* = \frac{\lambda - mu_t^N}{mu_t^R - \lambda} N_t + \frac{mu_t^R - mu_t^D}{mu_t^R - \lambda} D_t \tag{15}$$

The total number of banks are made up new, N_n and incumbent, N_e banks. The equity of banks can be written:

$$N_t = N_{et} + N_{nt} \tag{16}$$

The equity of existing banks is:

$$N_{et} = \theta \Delta_{t-1,t}^N N_{t-1} \tag{17}$$

and the equity of new banks is:

$$N_{nt} = \frac{\omega}{1-\theta}(1-\theta) Q_t S_{t-1} = \omega Q_t S_{t-1} \tag{18}$$

This is because new banks receive a fraction, $\omega/(1-\theta)$, of the current value of last period's total intermediated funds.

3.3 Intermediate Goods Producers

Intermediate goods producers borrow from banks to buy capital goods, which they combine with labour using a Cobb-Douglass technology. At the end of each period, intermediate goods producers use the borrowed funds to buy capital goods, K, at a price Q, used for production in the next period. Owing to this, the aggregate level of intermediate funds from commercial banks imposes an upper bound on the accumulation of capital used for production.

Assuming that the price of a capital good is equal to that of a financial claim, such that:

$$Q_t K_{t+1} = Q_t S_t \tag{19}$$

A Cobb-Douglass function governs the production of intermediate goods:

$$Y_{it} = A_t (U_t \xi_t K_t)^{\alpha} L^{1-\alpha} \tag{20}$$

where A is technology, U is the utilisation of capital and ξ is the quality of capital.

The first-order conditions for capital utilisation and demand for labour are:

$$P_t^M \alpha \frac{Y_t^M}{U_t} = \delta' \left(U_t\right) \xi_t K_t \tag{21}$$

and:

$$P_t^M (1-\alpha) \frac{Y_t^M}{L_t} = W_t \tag{22}$$

The expression for the profits of intermediate goods producers that are transferred to banks, R_t^K is written (Gross and Schiller, 2020):

$$R_t^K = \frac{\left[P_t^M \alpha \frac{Y_t^M}{\xi_t K_t} + Q_t - \delta\left(U_t\right)\right] \xi_t}{Q_{t-1}} \tag{23}$$

Since the quality of capital directly impacts banks' returns, a negative shock will lead to deterioration of commercial banks balance sheets and lead to loan defaults.

3.4 Capital Goods Producers

Capital goods producers are in the business of creating new and refurbishing capital goods. The cost of refurbishment is fixed at unity, and new goods are priced at Q. Profits from capital goods producers are transferred to shareholders, which are households, at each period. Each period I_t represents gross capital goods produced, and I^N denotes the difference between I and refurbished capital goods:

$$I_t^N = I_t - \delta(U_t)\xi_t K_t \tag{24}$$

The objective function of the capital goods producer can be written:

$$\max E_t \sum_{i=0}^{\infty} \beta^i \Lambda_{t,t+i} \left[\left(Q_{t+i} - 1\right) I_{t+i}^N - f\left(\frac{I_{t+i}^N + \bar{I}}{I_{t-1+i}^N + \bar{I}}\right)\left(I_{t+i}^N + \bar{I}\right)\right] \tag{25}$$

suggesting that capital goods producers maximise the sum of their future discounted profits. The function $f(.)$ is given the functional form $\frac{\eta_i}{2}\left[\frac{I_t^N+\bar{I}}{I_{t-1}^N+\bar{I}} - 1\right]^2$ (Gross and Schiller, 2020).

From the maximised objective function, the price of capital can be shown to be:

$$Q_t = 1 + f(\cdot) + \left(\frac{I_t^N + \bar{I}}{I_{t-1}^N + \bar{I}} \right) f'(\cdot) - E_t \beta \Lambda_{t,t+1} \left(\frac{I_{t+1}^N + \bar{I}}{I_t^N + \bar{I}} \right)^2 f'(\cdot) \tag{26}$$

The evolution of capital can be written as:

$$K_{t+1} = \xi_t K_t + I_t^N \tag{27}$$

3.5 Final Goods Producers

Final goods producers package intermediate goods and produce a final good. Final goods firms operate in a monopolistically competitive market, and output, Y_t, is a CES aggregator of differentiated final goods:

$$Y_t = \left[\int_0^1 Y_{ft}^{\frac{\varepsilon-1}{\varepsilon}} df \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{28}$$

Cost minimisation of the consumer yields the definitions for prices, P_t and the output of a final goods firm f, Y_{ft}:

$$Y_{ft} = \left(\frac{P_{ft}}{P_t} \right)^{-\varepsilon} Y_t \tag{29}$$

$$P_t = \left[\int_0^1 P_{ft}^{1-\varepsilon} df \right]^{\frac{1}{1-\varepsilon}} \tag{30}$$

From Gross and Schiller (2020), final goods produces are subject to nominal price rigidities *à la* Calvo (1983) such that only a fraction, $1 - \gamma$, of final goods firms can adjust prices to the optimal price P^* each period. Under this specification, firms maximise their profits by setting a markup over expected discounted future marginal costs. Their maximisation problem can be written:

$$\max E_t \sum_{i=0}^{\infty} \gamma^i \beta^i \Lambda_{t,t+i} \left[\frac{P_t^*}{P_{t+i}} \prod_{k=1}^{i} (\pi_{t+k-1,t+k}) - P_{t+1}^M \right] Y_{ft+i} \tag{31}$$

This yields the definition of final good prices:

$$P_t = [(1-\gamma)(P_t^*)^{1-\epsilon} + \gamma(\pi_{t-1}^{\gamma_\pi} P_{t-1})^{1-\epsilon}]^{\frac{1}{1-\epsilon}} \tag{32}$$

3.6 Monetary Policy

There is a monetary authority or central bank that sets the nominal interest rate on central bank funds i^{CB} following a standard Taylor Rule which follows the specification:

$$i_t^{CB} = (1-\rho)[(1+\bar{r}^{CB}) + \phi_\pi \pi_t + \phi_y y_t] + \rho i_{t-1}^{CB} \tag{33}$$

where ϕ_π and ϕ_y are the weights of inflation and output respectively in the central bank's response.

There is a premium imposed on the interest rates of bonds, CBDC and deposits enforcing the inequality relationship between the remuneration of the forms of saving $i^b \geq i^d \geq i^{\text{CBDC}}$. The nominal interest rate premia on deposits and bonds (the determination of the interest rate for the CBDC is discussed in section 3.7) are:

$$i_t^d = i_t^{CB} - \Delta_t^D \tag{34}$$

$$i_t^B = i_t^{CBDC} + \Delta_t^B \tag{35}$$

The real interest rate for bonds, deposits and CBDCs are given by the following Fisher relations:

$$1 + i_t^D = \left(1 + r_t^D\right)\left(1 + E_t \pi_{t,t+1}\right) \tag{36}$$

$$1 + i_t^{CBDC} = \left(1 + r_t^{CBDC}\right)\left(1 + E_t \pi_{t,t+1}\right) \tag{37}$$

$$1 + i_t^B \quad = \quad \left(1 + r_{t+1}^B\right)\left(1 + E_t \pi_{t,t+1}\right) \tag{38}$$

The central bank provides funding to banks; however, refinancing from the central bank is more expensive than from household deposits, given that $r^{CB} > r^D$. Because of this, commercial banks will only use central bank funds to fill the difference between the supply of deposits and the maximum level of refinancing F^* (Gross and Schiller, 2020).

3.7 Interest Rates on CBDCs

3.7.1 Simple Interest Rate Premium

In order to assess the implications of alternative interest rate schemas for the CBDC. In the base case, we assume that the CBDC has no restrictions, and the nominal interest rate is set as a fixed premium on the interest rate on central bank funds, analogous to the interest rate on deposits and bonds in the previous section, yielding:

$$i_t^{\text{CBDC}} = i_t^{CB} - \Delta_t^{\text{CBDC}} \tag{39}$$

3.7.2 Asset Elastic Interest Rate

Next, in the case of the asset elastic interest rate premium, we introduce a function $p(.)$ that is decreasing in the amount of CBDC held by an agent, such that:

$$i_t^{\text{CBDC}} = i_t^{CB} - \Delta_t^{\text{CBDC}} + p(CBDC_t) \tag{40}$$

the functional form for $p(.)$ is specified as $p(.) = \vartheta \frac{\overline{CBDC} - CBDC_t}{\overline{CBDC}}$ such that larger holdings of CBDC reduce the interest rate paid on the CBDC.[5] This specification follows a continuous implementation of an adjustable interest rate, as suggested in Kumhof and Noone (2018).

3.7.3 Panetta (2018) Style CBDC Holding Constraints

The first model with occasionally binding constraints introduced is a ceiling on CBDC holdings. From Panetta (2018), introducing a limit on the amount of CBDC that an agent can hold reduces the extent to which households are able to divert their bank deposits to CBDC, thus limiting the level of disintermediation in the financial sector.

[5] This specification allows the steady state of the model to remain the same as the simple interest rate rule.

In this regime, households are only able to hold a fixed proportion of their real deposit holdings in CBDC such that:

$$CBDC_t \leq \varsigma D_t \tag{41}$$

where ς is the proportion of deposits that represents the upper limit on CBDC holdings.

3.7.4 Bindseil (2020) Style Countercyclical Two-Tier Interest Rate

Bindseil (2020) proposes a two-tiered interest rate system, which provides a relatively attractive interest rate up to a threshold, above which the interest rate is made less attractive. There is an added countercyclical element, where the level of penalty imposed on holding the CBDC above the threshold rate is dependent on the level of stress in the financial sector. This two-tier model specifies the baseline fixed interested rate spread up to a ceiling of 10% above the steady-state holding level of CBDCs, above which the countercyclical interest rate penalty is imposed, such that:

$$i_t^{\text{CBDC}} = \begin{cases} i_t^{CB} - \Delta_t^{\text{CBDC}} - p(N_t) \ \text{ if } \ CBDC \geq \eta_(CBDC^{ss}) \\ i^{\text{CB}} - \Delta_t^{\text{CBDC}} \ \text{ otherwise} \end{cases} \tag{42}$$

where $P(N_t) = \frac{\bar{N}-N_t}{\bar{N}}\varsigma$, analogous to the determination the financial stress variable, ψ. This specification imposes a penalty to holding CBDC above the threshold, η, and the penalty is higher when there is more stress in the financial sector, determined by the net wealth of commercial banks.

3.8 Calibration

The model is calibrated following Gertler and Karadi (2011) and Gross and Schiller (2020), the parameterisation values can be found in Table 1. There are 25 parameters, 23 of which originate in Gertler and Karadi (2011) and Gross and Schiller (2020). The two new parameters are notable; they relate to the weight of the elasticity function in the asset-elastic interest rate (ϑ) and the proportion of deposits agents and can hold in CBDC (ς) in the holding ceiling model.

The interest rate premia on CBDC, bonds, deposits and Central Bank reserves are chosen in order to satisfy the relationship $r^B > r^D > r^{\text{CBDC}}$. From Gross and Schiller (2020), the interest rates for deposits and bonds are calibrated to roughly match the observed data specified in Gertler and Karadi (2011).

Table 1: Model Calibration

β	Household discount factor	0.990
h	Consumption habit formation	0.815
χ	Weight of Labour in utility	3.409
ϕ	Elasticity of Labour Supply	0.276
Ω_D	Elasticity of bank deposits in risk function	51.00
Ω_N	Weight of financial stress in risk function	0.050
Γ	Elasticity of real balances	-0.950
θ	Probability of bank survival	0.975
λ	Proportion of intermediated funds which are divertible	0.381
ω	Starting equity for entrant bankers	0.002
α	Capital Share	0.330
ζ	Elasticity of marginal depreciation	7.20
δ_i	Deprecation rate	0.025
ρ_k	Capital quality shock persistence parameter	0.660
η_i	Elasticity of Investment Adjustment Costs	1.728
ϵ	Elasticity of substitution	4.167
γ	Calvo Parameter	0.779
γ_π	Indexation parameter	0.241
ϕ_π	Response of Central Bank to Inflation	1.5
ϕ_y	Response of Central Bank to output gap	0.125
Δ^B	Interest rate premium between Central Bank reserves and bonds	0.001/4
Δ^D	Interest rate premium between Central Bank reserves and private bank deposits	0.001/4
Δ^{CBDC}	Base premium between Central Bank reserves and CBDC	0.02/4
ϑ	Weight of elasticity function in CBDC interest rate	0.00002
ς	CBDC holding limit in terms of deposit holdings	0.390

4 Results

4.1 Baseline Model

A negative capital quality shock is introduced to explore the implications of introducing a CBDC. The shock's variance is set to imply a 5% decrease in capital quality, sufficient to lead to deterioration of bank balance sheets.[6] This negative capital quality shock reduces the potential output from intermediate firms, reducing profits transferred to private banks and ultimately loan defaults. Consequently, bank equity is reduced and, from the risk function, ψ, households perceive greater risk in the financial system, thus transfer their wealth to less risky assets. Figure 1 shows the impulse responses of a capital quality shock in the case of the baseline model, where no CBDC is present, and in the case of a CBDC introduced with no restrictions on holding. The models presented in this paper assume that a CBDC will bear remuneration, that is, a steady-state positive interest rate. A positive nominal interest rate causes the CBDC to be a closer substitute to bank deposits than the 'token' style non-interest-bearing design.[7] As a closer substitute, households are more likely to transfer their holdings to CBDC from deposits when they perceive more risk in the financial sector.

In the benchmark CBDC model, where no restrictions are placed on holding CBDC, and the interest rate follows a fixed spread from the central bank policy rate, CBDC

[6]This decrease in capital quality is calibrated in order to provide a shock similar to the magnitude of the financial crisis Gross and Schiller (2020).

[7]There is a distinction between account-based and token-based CBDC structures. An account-based system refers to a collection of accounts with an owner and a corresponding balance; agents must prove they have authority over the account for transactions to occur. Token-based systems represent a ledger of assets; the asset has an assigned owner, and in order for a transaction to occur, an agent must prove that they own each token (Bank of England, 2020).

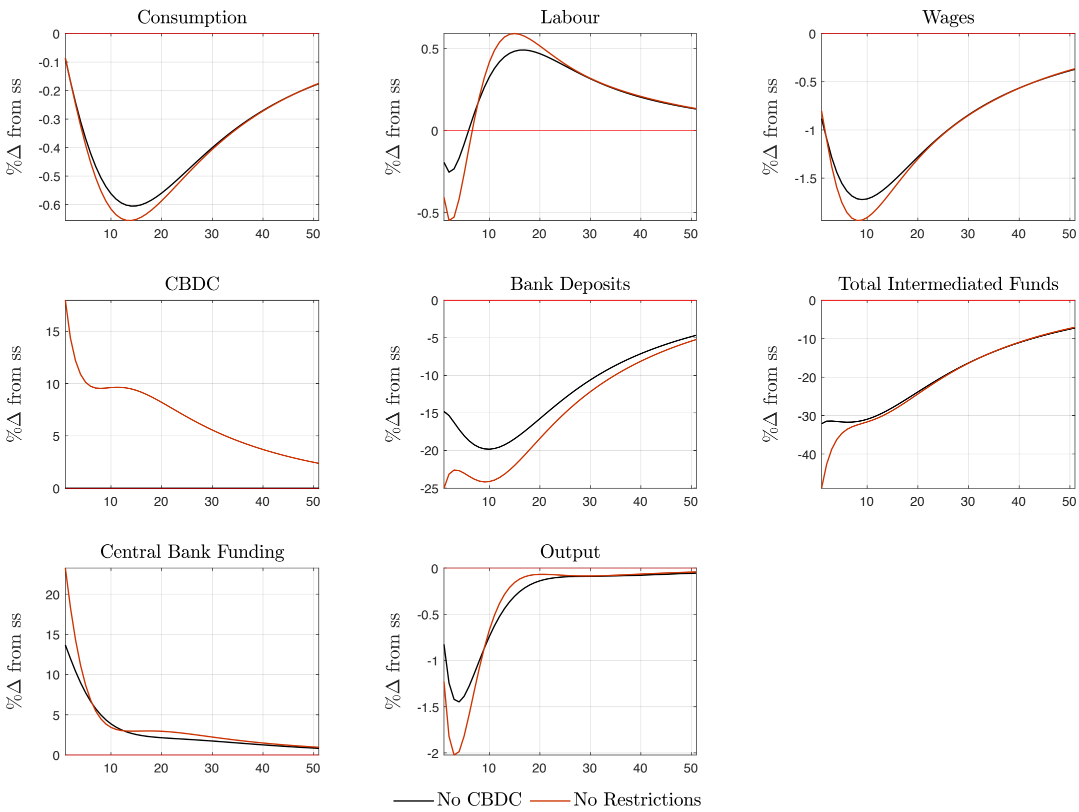
holdings rise to 18% above steady-state. Commercial bank deposits fall to -25% below steady-state compared to -19.8% when CBDCs are not available. Further, in the 'no-CBDC' economy, total intermediated funds fall to -32.1% below steady-state, compared to the drastic fall to -48.9% when CBDCs are present. This result is stark, suggesting that the presence of CBDCs greatly exacerbates the deterioration of commercial bank's balance sheet health in crises, as households move their holdings out of bank deposits to the newly available CBDC.

When the agent faces the opportunity to transfer their holding to CBDC, it is noticeable that the decrease in consumption and output is more severe, and bank deposits are reduced further than in the case where CBDC is not available. As such, we see a far more severe disintermediating effect when CBDC is introduced. However, it is important to note that there is still a significant drop in bank deposits even when agents cannot transfer their wealth to CBDC; there is still a decrease in bank deposits as households increase their bond holdings.

In response to this reduction in bank deposits, the Central Bank is forced to step in, increasing the amount of refinancing to make up the difference from lost deposits; however, this implies further losses of bank profits, owing to the higher interest rate on central bank funds compared to deposits.

The financial accelerator effect that arises from disintermediation becomes clear when inspecting the impulse responses for consumption and output. In the 'no-CBDC' economy, output initially falls to -0.8% before falling further to -1.4%; this second drop can be explained by the financial accelerator that arises from bank defaults. We see that when the CBDC is introduced, both the initial fall in output and the financial accelerator effect is exacerbated, initially falling to -1.3% then to -2%. Similarly, the CBDC exacerbates the fall in output, leading to a 0.05 percentage point decrease in consumption at its lowest, from -0.6% to -0.65%.

Figure 1: Baseline model vs. CBDC with no holding restrictions



4.2 Asset-Elastic Interest Rate

This section explores the implications of a CBDC interest rate structure that is elastic to the quantity of an agent's CBDC holdings. This follows the adjustable interest rate specification from the Kumhof and Noone (2018) design principles. Schmitt-Grohé and Uribe (2003) introduce the concept of a debt-elastic interest rate premium that circumvents indeterminacy problems. We can provide a linear approximation to both the holding ceiling and two-tier interest rate system by introducing an asset-elastic interest rate. While this form of policy may be technically challenging to implement in the real world, it provides an instructive benchmark as a generalised form of anti-disintermediation policy.

Figure 2 shows the impulse responses for the asset-elastic interest rate compared with the no-CBDC economy and the CBDC with no restrictions. When the initial capital quality shock hits in period 0, the decline in bank profits causes agents to assign more risk to their commercial bank deposits, requiring a larger spread between them and the CBDC, thus shifting their deposits to CBDC and bonds. As the initial shift to CBDC peaks, the asset elastic interest rate decreases the nominal interest rate on CBDC, making deposits relatively more attractive, reducing the peak CBDC holdings to 11.7% above the steady-state. This constitutes a reduction in CBDC holdings of 6.3 percentage points compared to when no restrictions are present.

This interest rate scheme reduces the amount of CBDC held and allows the CBDC holdings to return to the steady-state faster than in the no-restriction model. Concerning bank deposits, the asset elastic interest rate causes a lower peak in the decline of bank deposits by around 2.5 percentage points, further, as the elastic interest rate initiates, bank deposits return to the 'no-CBDC economy' model path after 25 periods, far quicker than in the no restriction model. Further, total intermediated funds fall to -45.2% below the steady-state, compared to the -48.9% in the benchmark model. This suggests that the asset elastic interest rate structure reduces disintermediation by around 3.7 percentage points. Household's deposits with commercial banks fall to -23.1% below steady-state. This is a reduction of 1.8 percentage points compared to the no restriction model.

The shock leads to a fall in inflation, falling -0.15% from the steady-state in the baseline model and -0.2% in the CBDC economies. This fall in inflation causes the central bank to respond by lowering the policy rate. This reduction in the policy rate follows through with the nominal rate in deposits. Given the already high level of risk assigned to bank deposits, this new, lower rate on deposits causes deposits to be even more unattractive to agents, leading to the second fall in total bank deposits at period 10.

Figure 2: CBDC Asset Elastic Interest Rate

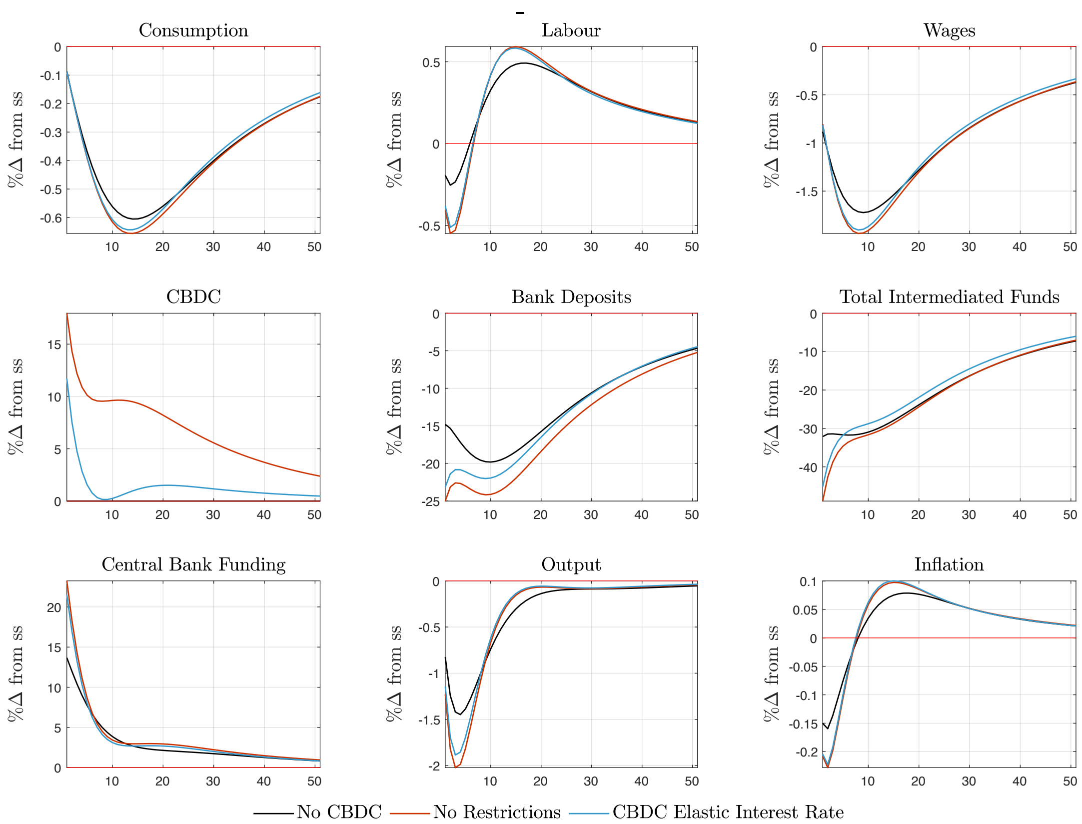
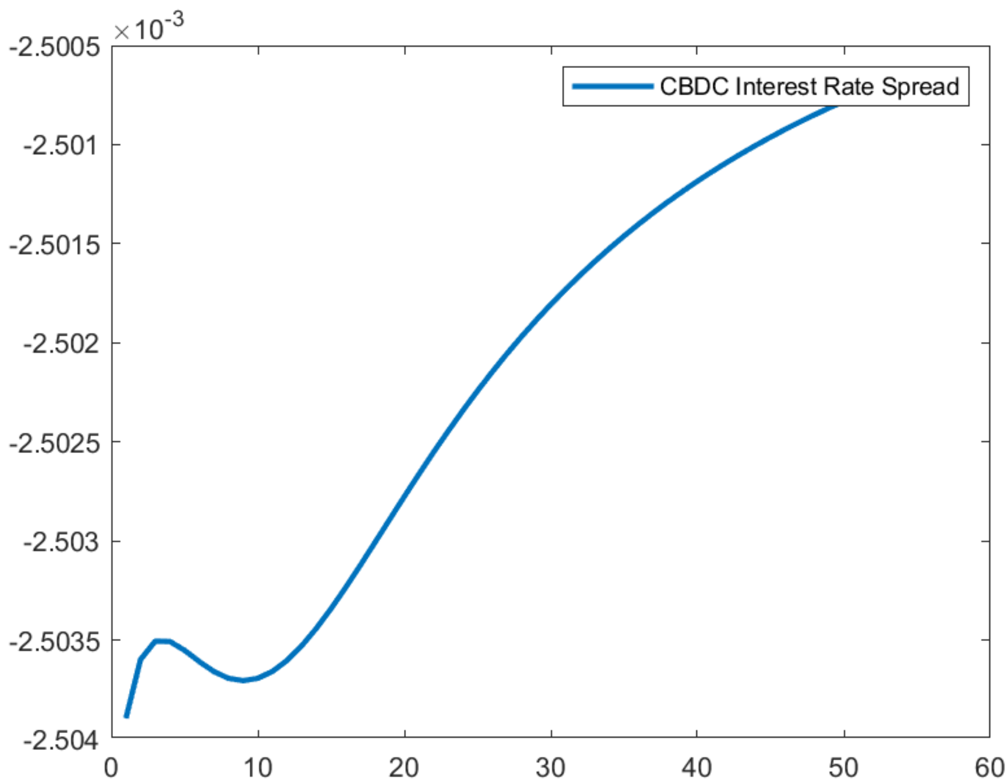


Figure 3 shows the interest rate spread between CBDC holdings and deposits under the asset-elastic interest rate structure. As the agent increases their interest rate holdings, they face an increasing spread between deposits and CBDC, thus making

CBDC relatively less attractive the more the household holds. After the initial shock, the agent wishes to keep a higher level of CBDC, thus lowering the interest rate they receive on their holdings. Consequently, this lower interest rate causes the agent to increase their CBDC holdings less than in the case of the 'no-restriction' model.

Figure 3: CBDC / Deposits interest rate spread under asset-elastic interest rate structure



4.3 Holding Ceiling

Panetta (2018) suggests that the Central Bank may impose a ceiling on CBDC holdings in an attempt to mitigate the probability and effects of a 'digital' bank run, where households take their deposits out of banks and move them into the CBDC. Importantly, this policy would impose not only economic but also technical implications. Chiefly, with a hard ceiling imposed on CBDC holdings, transactions would have to be pre-checked and confirmed to ensure that the recipient has the headroom in their account to receive the payment without breaching the limit.

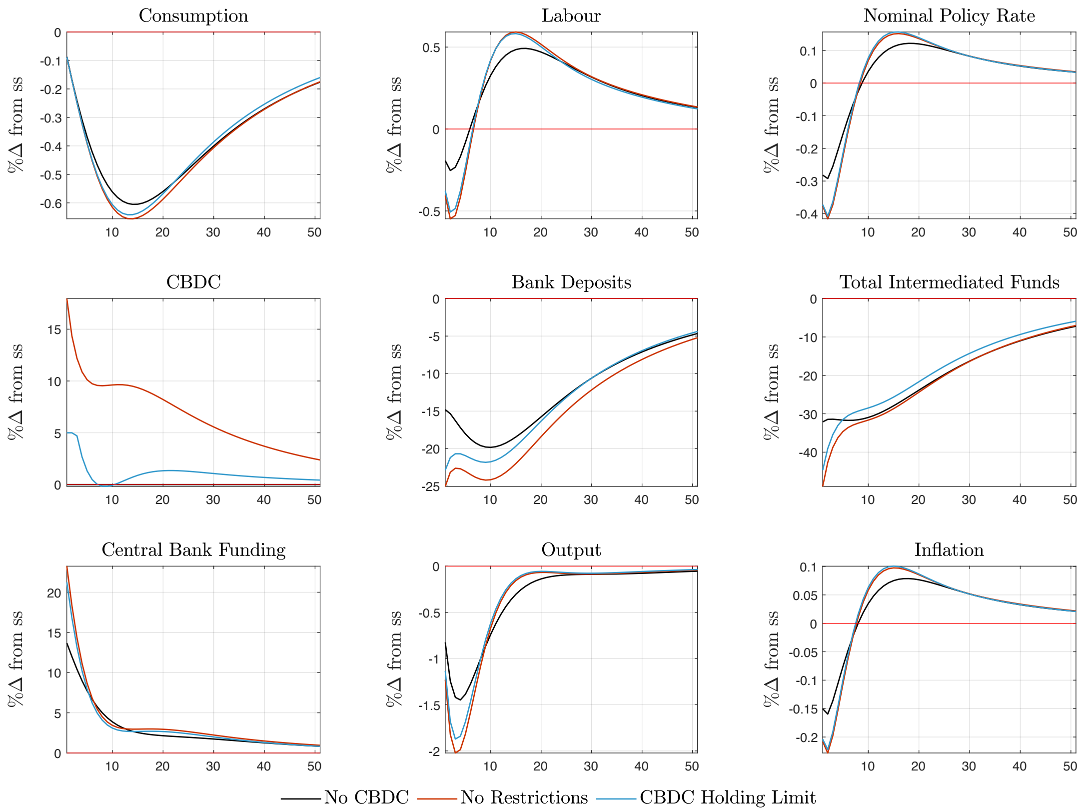
In this section, the CBDC model is extended by adding a moving ceiling such that agents can hold a fixed fraction of their wealth in bank deposits in CBDC. Using the OccBin package (Guerrieri and Iacoviello, 2015), which uses a first-order perturbation algorithm in order to simulate models with occasionally binding constraints, Figure 4 shows the impulses responses.

The holding ceiling significantly reduces the spike in CBDC holdings after the initial shock. Additionally, the level of CBDC holdings quickly returns to steady-state after ten periods before a small deviation above steady-state. While the holding ceiling drastically impacts the level of CBDC agents opt to hold, disintermediation is only reduced by approximately 4.2 percentage points, as agents choose to move most of their holdings to bonds.

Total intermediated funds fall to 45% below steady-state, suggesting that the holding ceiling reduces disintermediation by about five percentage points, compared to the 50% fall below steady-state when no CBDC restrictions are present. Interestingly, the CBDC holding limit leads to total intermediated funds to return to the steady-state quicker than the 'no-restriction' model and even the 'no-CBDC' economy.

The holding ceiling additionally reduces the decrease in output, consumption and labour supply. Focussing on output, the introduction of the CBDC returns output to steady-state quicker than in the economy without CBDC, and the holding-ceiling reduces the fall from -2% to -1.8%.

Figure 4: CBDC Holding Ceiling IRFs



4.4 Two-Tiered Interest Rate

Finally, the impulse responses shown in figure 5 display the results of a two-tiered interest rate as proposed by Bindseil (2020). In this model, the agent faces a fixed spread when holding CBDC below a certain threshold and a penalising interest rate above the threshold.[8] The impulse responses show that while this interest rate structure reduces the flight to CBDC after the capital quality shock and reduces the level of disintermediation, it has relatively low effects on the reduction in output and consumption associated with the shock, suggesting that the two-tier interest rate has less stabilising power than some of the other interest rate structures proposed.

After the initial shock, CBDC holdings peak at 8%, considerably lower than the 15% peak in the 'no-restriction' model. After CBDC holdings pass the threshold level, the countercyclical interest rate commences, causing the agent to lower their CBDC holdings quickly. Additionally, this lower peak hastens the return to the steady-state level. Flight from bank deposits is mitigated by around one percentage point, from 25% in the 'no-restriction' model to 24% with the two-tier system. This suggests that, while there is some reduction in the flight from bank deposits, the two-tiered interest rate system is not as effective as the elastic interest rate and holding limit system. Total intermediated funds fall to -48% below the steady-state value, implying that the tiered interest rate structure reduces disintermediation by around two percentage points. This suggests that the two-tier system is slightly less effective than the holding ceiling policy.

This result is somewhat intuitive, while the mitigation from the two-tiered interest rate is largely governed by its two primary parameters (namely the threshold level and the level of penalty applied to holdings above the threshold), with a positive interest rate spread applied above the threshold, it is intuitive that the reduction in CBDC holding, and consequently disintermediation, will be less than hard upper-

[8]In this model, the threshold is set at 10% above steady-state CBDC holdings. In practice, thresholds and interest rates should be based on larger scale models of disintermediating economic events.

bound on CBDC holdings. Additionally, compared to the asset-elastic interest rate, the two-tiered system allows a range of non-penalised holdings, whereas the asset-elastic interest rate reduces the interest rate at any level of positive holdings.

Figure 5: Two-tiered Interest Rate IRFs

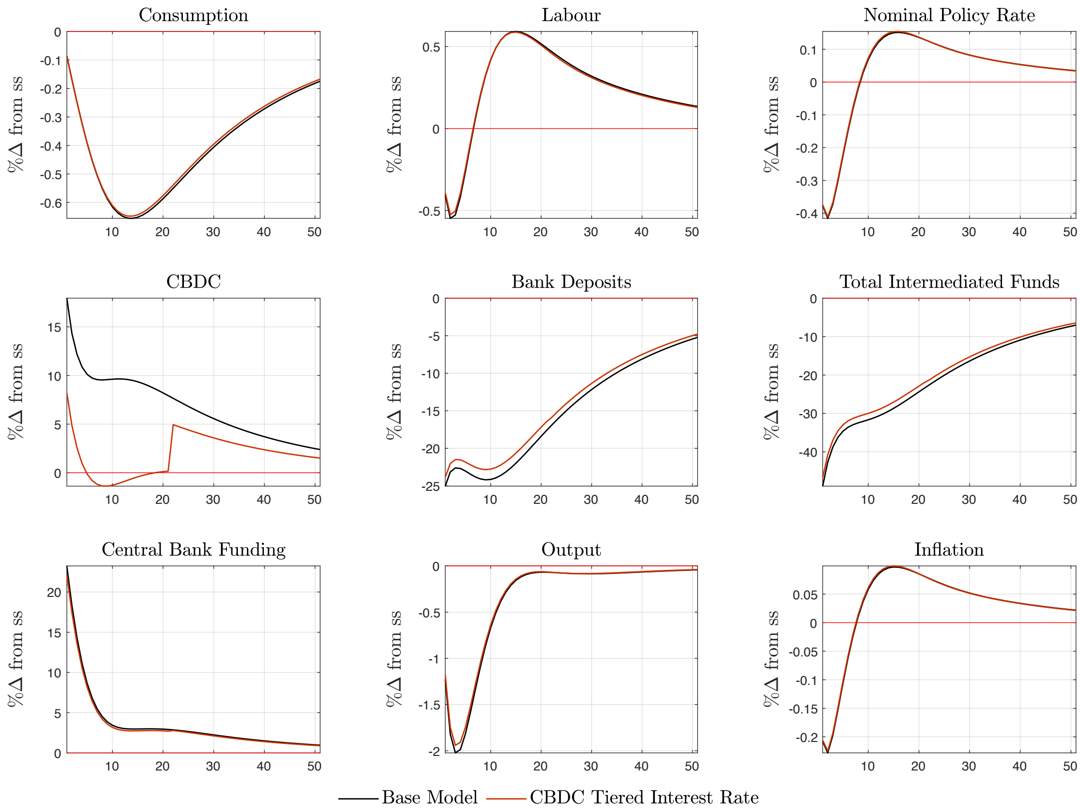
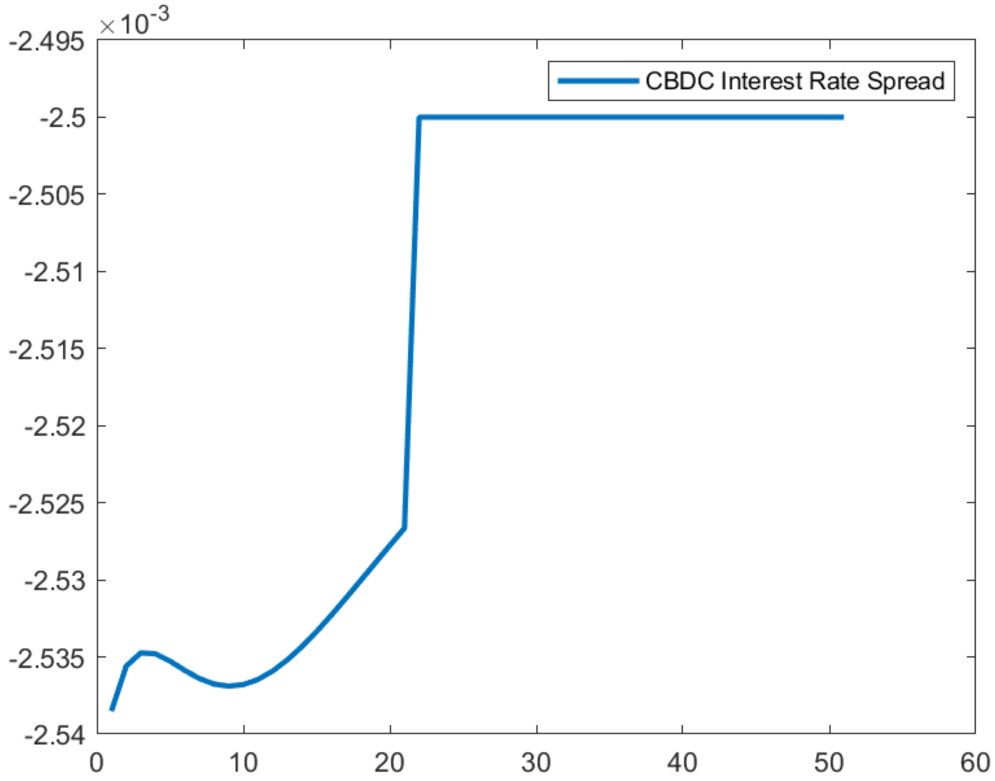


Figure 6 shows the spread between the nominal interest rate on CBDCs and the deposits, thus illustrating the implementation of the countercyclical two-tiered interest rate. After the initial shock, the optimising household wishes to transfer their bank deposits to CBDC holdings, taking the consumer above the interest rate threshold. The countercyclical interest rate scheme increases the spread between the CBDCs and deposits when there is increased stress in the financial sector. From figure 6 we can see that the interest spread follows the decline in deposits when CBDC holdings are above the threshold before returning to the fixed interest spread when CBDC holds fall back below the threshold.

Figure 6: CBDC / Deposit Interest Rate Spread under countercyclical two-tier interest rate structure



4.5 Model Comparison

Figure 7 shows the impulse responses for each of the interest rate structures studied, alongside the 'no-CBDC economy' model and 'no-restriction' model; table 2 gives an overview of disintermediation under the various interest rate schemes. It is evident that each of the interest rate specifications changes the dynamics of CBDC holdings;

however, all the models have their intended effect of reducing the 'flight-to-CBDC' following a negative capital quality shock.

While there is a relatively large variation in the impulse response functions for CBDC holdings, this does not translate into a large variation in total disintermediation. This stems from the financial accelerator effect that arises following the introduction of the CBDC. When agents convert their deposits to CBDC, commercial banks are forced to reduce their loan issuance if the central bank does not make up the difference in refinancing. Without access to this credit, intermediate capital producers cannot buy capital, thus reducing output further. In terms of mitigating disintermediation, the CBDC holding limit and asset-elastic interest rate offer very similar efficacy; however it should be noted that in order to achieve this level of anti-disintermediation, the level of elasticity has to be relatively high, forcing CBDC holdings to deviate below the steady-state level, while the holding ceiling allows for a 5% to 10% increase in CBDC holdings above steady-state - which is preferable due to the CBDC's confidence improving effects. The two-tiered interest rate also provides an anti-disintermediating force following a capital quality shock; however, it is 1% to 3% less effective than the holding-ceiling and elastic interest rate specifications. While these reduce overall levels of disintermediation, the parameters are not set high enough to mitigate the financial accelerator effect, implied by the significant fall in output compared to the baseline model.

As discussed, while the holding-ceiling specification shows a higher anti-disintermediating effect compared to the two-tier system, technical limitations and other considerations will also play a large factor in the decision to implement these policies. While setting an upper bound on CBCD holds is technically trivial, it introduces other considerations that could disrupt financial transactions. Specifically, if a transaction violates an account's holding limit, then the transaction will be rejected. In order to mitigate this kind of transaction problem, limits will have to be checked before transactions take place, bringing about significant friction - not only in the network but also for the parties involved. This type of restriction will likely lead to inefficiency that is not desirable from an infrastructure or user perspective.

Furthermore, the two-tier interest rate boasts additional benefits, increasing its attractiveness. Firstly, central banks have precedent using a two-tiered remuneration system, such as the Eurosystem's tiering systems for public institutions' accounts with the central bank (ECB, 2014). The two-tiered system allows that, even in the case of a large scale financial or economic crisis, remuneration of CBDCs does not all have to be negative – allowing monetary authorities to circumvent some common criticism (e.g., expropriation of money holders) (Bindseil, 2020).

There is scope for additional policies with a two-tier interest rate which make any CBDC more useful or malleable towards policy objectives. For example, tier-one allowances could be heterogeneous between agents, such as setting the tier one holding allowance of firms to zero or tuned more finely towards individual firm's needs to receive payments from households. These extensions allow the designers of CBDCs to more closely manage the CBDC towards providing the benefits that CBDCs allow whilst mitigating the negatives.

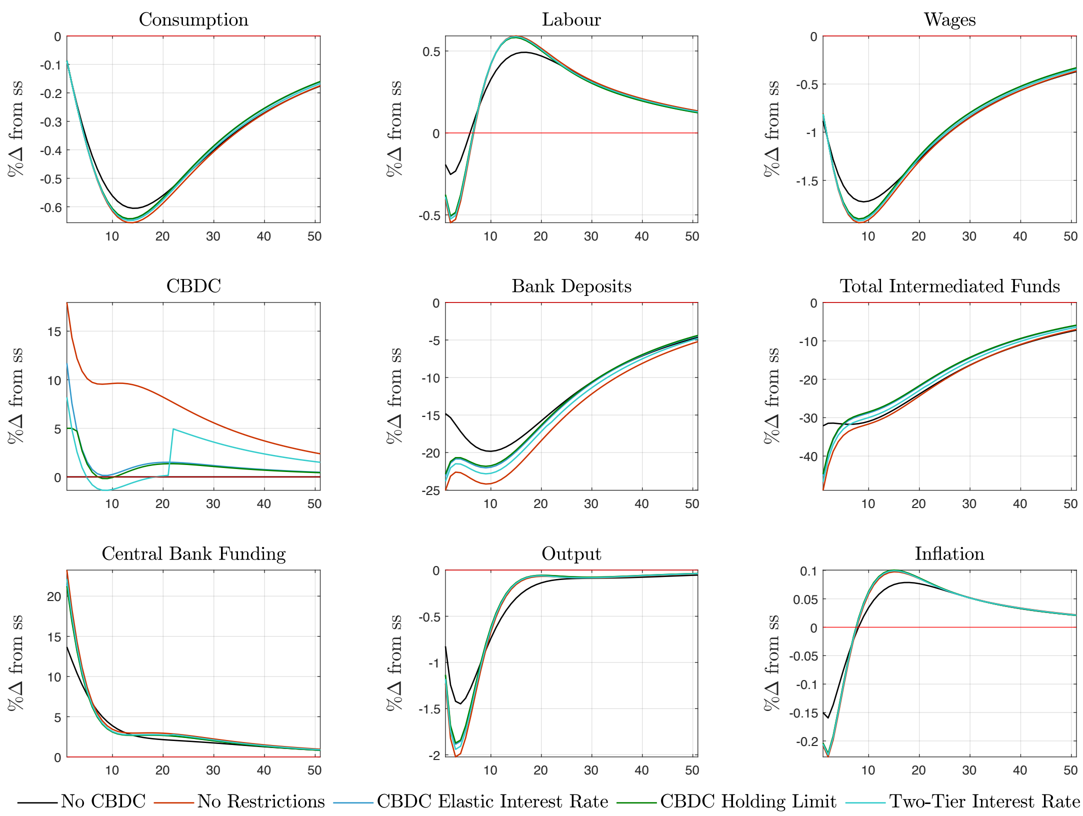
Barrdear and Kumhof (2021b) complements the findings of this paper, showing that a countercyclical CBDC interest rate rule can also help to stabilise the business cycle above stabilisation provided by countercyclical policies on the interest rate of

Table 2: Results summary

Policy	Total Intermediated Funds	Anti-disintermediating effect
Fixed spread	-48.9%	-
Asset-elastic	-45.2%	3.7pp
Holding ceiling	-44.7%	4.2pp
Two-tier	-46.7%	2.2pp

central bank reserves. Further, they show that when there is lower substitutability between CDBCs and bank deposits, CBDC interest rules have to be more aggressive to deliver the same stabilising effect.

Figure 7: IRF Comparison



4.5.1 Welfare Effects

This section explores the welfare effects of the introduction of CBDCs, the holding-ceiling and the two-tier interest rate model. Table 3 provides a summary of the results. The derivation of the recursive welfare function can be found in appendix B. Firstly, introducing a CBDC compared with the 'no-CBDC' economy results in a 4.94% increase in total welfare.

The welfare analysis indicates that the countercyclical two-tier interest rate yields an 8.73% welfare gain compared to the 'no-CBDC' economy and a 3.99% increase in welfare compared to the CBDC with no restrictions. Finally, the holding ceiling model resulted in a 13.1% increase in welfare when evaluated against the 'no-CBDC' economy and an 8.58% increase in welfare compared to the no-restrictions model.

Table 3: Welfare improvements by policy

	Welfare gain relative to	
Policy	**No Restriction Model**	**No CBDC Model**
No restriction	-	4.94%
Two-tier	3.99%	8.73%
Holding ceiling	8.58%	13.10%

The welfare analysis suggests that while the introduction of the CBDC allows brings about a welfare gain over the baseline 'no-CBDC' economy model, the two anti-disintermediation policies both increase welfare above and beyond the CBDC without restrictions. Of the two policies, the holding ceiling policy generates the greatest welfare improvement.

5 Conclusion

With over 80% of central banks considering developing a central bank digital currency (Bank for International Settlements et al., 2020), there is increasing focus on both the benefits and the economic implications that may arise from their introduction. While there is a growing base of literature on the macroeconomic effects of CBDCs, particularly concerning the potential for financial disintermediation in times of crisis, there has been little focus on exploring the economic implications and relative efficacy of the various design structures that have been proposed to mitigate disintermediation.

This paper contributes to the existing literature by analysing the most popular designs that have been proposed to mitigate the risk of financial disintermediation stemming from negative economic shocks in a DSGE framework. Three potential design schemes are analysed by introducing CBDCs into a DSGE model with financial intermediaries: a CBDC asset elastic interest rate, a hard ceiling on CBDC holdings and a countercyclical two-tier interest rate. The impulse responses analysed result from a negative capital quality shock, calibrated to represent a downturn of a similar magnitude to that of the global financial crisis.

The analysis finds that, although each policy alters the level of the agent's CBDC holdings quite significantly, the effect of disintermediation is fairly similar for them all. The best-performing policy, somewhat intuitively, is the holding ceiling, reducing the fall in bank's equity and total intermediated funds by 2.5 percentage points and 4.2 percentage points, respectively. Additionally, the holding ceiling policy reduces the peak CBDC holdings by 15 percentage points, from 20% to 5%. The two-tier model reduces intermediation by 2.2 percentage points compared to the baseline model. Finally, the asset-elastic interest rate policy reduces the fall in total intermediated funds by 3.7 percentage points.

While having the highest antidisintermediation effect, the holding ceiling is also the most restrictive policy and introduces several unwanted features into the design of the CBDC and its payment network. The countercyclical two-tier interest rate and the asset-elastic interest work in similar methods by dynamically adjusting the spread between the interest rate on deposits and that of the CBDC, causing higher levels of risk in the financial sector to trigger a 'run-to-CBDC'. The asset-elastic interest rate, while being the easiest policy to model, would provide significant implementation challenges. Finally, the countercyclical interest rate has attractive properties in allowing designers to prescribe different thresholds for different agents, perhaps making it the most attractive policy solution.

The welfare effects of the policies are also analysed, compared to the baseline welfare of the household in the model without a CBDC, introducing CBDCs with no restrictions improves welfare by 4.94%. The two-tier interest rate and holding ceiling model yield even greater welfare improvements, 13.10% and 8.73%, respectively.

Overall, the models suggest that all design proposals have an anti-disintermediating effect by increasing the bank-run equilibria. Further, these policies can help to increase welfare compared to the no-CBDC economy. However, questions remain, the exact parameterisation of the policies will be important. For example, what should be the threshold and the level of countercyclical variation under a two-tier interest rate policy, or what should the upper-bound on holdings be in a Panetta (2018) style policy? While many important questions remain, this work goes some way to addressing the fundamental questions of what policy is the best approach to managing disintermediation risk following the introduction of a CBDC. Further, richer models should be developed, particularly when exploring the implications of the countercyclical two-tier interest rate policy. In particular, a model with heterogeneous agents could be implemented to analyse the calibration of the threshold and how aggressive the countercyclical element responds to macroeconomic conditions.

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A Derivation of Household First Order Conditions

The optimisation problem of the household can be written:

$$\max E_t \sum_{i=0}^{\infty} \beta^i \left\{ \ln\left(C_{t+i} - hC_{t+i-1}\right) + \frac{\Upsilon}{1+\Gamma}\left(D_{t+i} + CBDC_{t+i}\right)^{1+\Gamma} - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \right\} \tag{43}$$

subject to their budget constraint:

$$C_t + D_t + CBDC_t + B_t = w_t L_t + F_t + \left(1 + r_{t-1}^D\right)\psi_{t-1} D_{t-1} + \left(1 + r_{t-1}^{CBDC}\right) CBDC_{t-1} + \left(1 + r_{t-1}^B\right) B_{t-1} \tag{44}$$

The Lagrangian of this problem reads:

$$\begin{aligned}
\mathcal{L} = E_t \sum_{t=0}^{\infty} \beta^i & \Bigg[\ln\left(C_t - hC_{t-1}\right) + \frac{\Upsilon}{1+\Gamma}\left(D_t + CBDC_t\right)^{1+\Gamma} - \frac{\chi}{1+\phi} L_t^{1+\phi} \\
& - \lambda_t \left[C_t + D_t + CBDC_t + B_t - w_t L_t - \Pi_t \right. \\
& - \left(1 + \tau_{t-1}^D\right)\left(1 - \left(\frac{D_{t-1}}{F_{t+1}^*}\right)^{\Omega_D} - \frac{N - N_{t-1}}{N}\Omega_N\right) D_{t-1} \\
& \left. - \left(1 + r_{t-1}^{CBDC}\right) CBDC_{t-1} - \left(1 + r_{t-1}^B\right) B_{t-1} \right] \Bigg]
\end{aligned} \tag{45}$$

To derive the first order conditions for the household's problem, differentiating the Lagrangian with respect to consumption C_t, D_t, L_t, CBDC_t and B_t yields:

$$\frac{\partial \mathcal{L}}{\partial C_t} = 0 \rightarrow \left(C_t - hC_{t-1}\right)^{-1} - \beta h \left(C_{t+1} - hC_t\right)^{-1} = \lambda_t \tag{46}$$

$$\frac{\partial \mathcal{L}}{\partial L_t} = 0 \rightarrow \chi L_t^{\phi} + \lambda_t = w_t \tag{47}$$

$$\frac{\partial \mathcal{L}}{\partial D_t} = 0 \rightarrow \Upsilon \left(D_t + CBDC_t\right)^{\Gamma} = \lambda_t \tag{48}$$

$$\frac{\partial \mathcal{L}}{\partial CBDC_t} = \Upsilon \left(D_t + CBDC_t\right)^{\Gamma} - \lambda_t + \beta \lambda_{t+1} \left(1 + r_t^{CBDC}\right) \tag{49}$$

$$\frac{\partial \mathcal{L}}{\partial B_t} = -\lambda_t + \beta \lambda_{t+1} \left(1 + r_t^{B}\right) \tag{50}$$

Combing equation (46) and (47) yields the Euler Equation:

$$\frac{1}{C_t - hC_{t-1}} - \frac{\beta h}{C_{t+1} - hC_t} w_t = \chi L_t^{\phi} \tag{51}$$

B Derivation of the Recursive Welfare Function

From the utility function for households:

$$U_t = \sum_{i=0}^{\infty} \beta^i \left\{ \ln\left(C_{t+i} - hC_{t+i-1}\right) + \frac{\Upsilon}{1+\Gamma}\left(D_{t+i} + CBDC_{t+i}\right)^{1+\Gamma} - \frac{\chi}{1+\phi} L_{t+i}^{1+\phi} \right\} \tag{52}$$

a function for the present discounted value of lifetime welfare can be written:

$$w(t) = U_t + \beta w(t+1) \tag{53}$$

Because this function is recursive, it can be written as:

$$w(t) = U_t + \beta\Big(U_{t+1} + \beta\big(U_{t+2} + \cdots\big)\Big) \tag{54}$$

denoting steady-state values by dropping the time index and expanding this function yields:

$$\begin{aligned} w &= U + \beta w \\ &= U + \beta\big(U + \beta w\big) \\ &= U + \beta U + \beta^2 w \\ &= U + \beta U + \beta^2 (U + \beta w) \\ &= U + \beta U + \beta^2 U + \beta^3 U + \cdots + \beta^n U \\ &= \sum_{n=0}^{\infty} \beta^n U \end{aligned} \tag{55}$$

which is a geometric series that can easily be solved numerically for the steady-state.

Acemoglu et al. (2020); Kahneman and Tversky (1987)