CBDC, Financial Disintermediation and Financial Fragility

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Abstract

A central bank digital currency (CBDC) competes with bank deposits as a means of payment. This paper studies a limit on the amount of CBDC that a household may hold, in a model that places banks with an endogenous leverage constraint in the centralized market of a New Monetarist economy. Households pay with cash, deposits or CBDC in decentralized meetings that differ in what sellers accept. Deposits are a cheap source of funds for banks because they are used for payments, and the limit determines how much of that advantage CBDC takes away. In a calibration to the United States, each dollar of CBDC lowers deposits by $1.21. A limit of $6,000 per person lowers deposits by 12.7 percent, the capital stock by 8.4 percent and consumption by 2.6 percent. The same adjustment makes banks safer: leverage falls from 6.00 to 5.76, and banks hold 17.4 cents of net worth for each dollar of assets, up from 16.7. The response of the economy to shocks is almost unchanged. Bank runs become slightly harder to trigger as the limit rises, up to the limit at which deposits stop carrying a liquidity premium, $13,164 per person. Above it they become easier to trigger, because the CBDC that households hold slows the recovery of banks after a run.

Keywords: central bank digital currency, bank disintermediation, financial fragility, bank runs, liquidity premium, monetary search.
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1 Introduction

The majority of central banks are considering issuing a central bank digital currency (CBDC), according to the latest survey of the Bank for International Settlements (Illes, Kosse and Wierts 2025). Although a CBDC is not intended to replace cash, it is widely expected to be a more efficient and safer means of payment, and possibly to support financial stability. Implementing one at scale, however, raises concerns about its effect on the banking sector. One concern in particular is that, because a CBDC competes directly with bank deposits, its issuance would raise the cost to banks of raising deposits, contributing to disintermediation and, in turn, to lower output. Existing estimates suggest such effects could be sizable: the European Central Bank's own scenario analysis finds that a €3,000 holding limit would displace €647 billion of deposits (Adalid et al. 2022), while Whited, Wu and Xiao (2023) estimate that each dollar of CBDC replaces roughly eighty cents of deposits in the United States.

A second concern is that a CBDC would make bank runs more likely, since a claim on the central bank is a more attractive destination for fleeing depositors than cash. Bidder, Jackson and Rottner (2025) find that introducing a CBDC roughly doubles the probability of a run, from 1.28 to 2.51 percent, and that a holding limit restores it to close to its original level, and Williamson (2022b) reaches a similar conclusion in a model where bank insolvency can trigger panics. The direction is not settled, however: Keister and Monnet (2022) argue that a CBDC also makes deposit outflows observable to the central bank in real time, allowing weak banks to be identified earlier and leading banks to take less maturity risk to begin with.

This paper builds a quantitative model to assess both financial disintermediation and financial fragility. It finds that a CBDC does disintermediate banks, and that the same mechanism makes the banking system safer. The model places a banking sector in the style of Gertler and Karadi (2011) inside the monetary framework of Lagos and Wright (2005), in which payments are subject to explicit frictions. Combining the New Monetarist framework with a dynamic stochastic general equilibrium (DSGE) model makes it possible to capture the role of deposits and CBDC as means of payment and, at the same time, to study how they interact with the business cycle. This shows the role that CBDC plays in financial disintermediation and in financial fragility.

Each period divides into two markets. In the centralized market, banks raise funds by issuing deposits to households. Firms borrow from banks to purchase capital for production and sell their output to households. Households decide how much to consume, how much capital to hold directly, which involves a management cost, and which portfolio of cash, deposits and CBDC to bring into the decentralized market. In the decentralized market, trade is bilateral and anonymous, and settlement requires an asset carried out of the centralized market: cash, deposits or CBDC. With some probability a household enters a meeting, as a buyer or as a seller. There are three types of meeting. In the first type,

sellers accept only cash. The share of cash-only meetings is small, because cash settles only a small share of transactions. In the second type, sellers accept only CBDC. This type represents transactions in which CBDC can be used and a card payment cannot, such as a payment without a network connection. In the third type, sellers accept both deposits and CBDC. There is no meeting in which deposits are accepted and CBDC is not: any seller willing to take bank money also takes the central bank's. Within the third type deposits and CBDC are added together, and therefore CBDC competes with deposits directly as a perfect substitute. The decentralized market gives each of the three assets, cash, deposits and CBDC, a liquidity premium. The liquidity premium on deposits allows banks to raise funds at a lower cost. That banks pay materially less than market rates on deposits is a well-documented feature of the data (Drechsler, Savov and Schnabl 2017).

Overall, this paper finds that the introduction of CBDC does lead to financial disintermediation, but that at the same time it lowers financial fragility and leaves the response of the economy to shocks almost unchanged. More specifically, CBDC competes away the liquidity premium on bank deposits and therefore raises the return that households require on deposits, which raises the cost of funds for banks. As a result, deposits fall and the balance sheets of banks shrink. Each dollar of CBDC lowers deposits by \$1.21, more than the eighty cents estimated by Whited, Wu and Xiao (2023). The effect on banks is largest when households hold CBDC worth \$13,164 each. At that amount the liquidity premium on bank deposits is zero, and banks can no longer raise funds below the market rate. Deposits are then 28 percent lower than without CBDC, the capital stock 19 percent and consumption 6 percent. At the same time, the leverage of banks falls from 6.00 to 5.43. With a holding limit in place, the disintermediation effect of CBDC can be contained. A limit of \$6,000 per person roughly halves it: deposits fall by 12.7 percent and the capital stock by 8.4 percent. Leverage falls to 5.76, and banks hold 17.4 cents of net worth for each dollar of assets, against 16.7 cents without CBDC. Regarding bank runs, no run is possible in any steady state, with or without CBDC. A holding limit slightly increases the size of the shock that is required to make a run possible: by 1.3 percent with a limit of \$6,000 and by 2.7 percent with a limit of \$12,000. This holds up to the amount at which the liquidity premium on deposits disappears. With more CBDC than that, a run becomes easier to trigger, because the CBDC that households hold slows the recovery of banks after a run.

Methodologically, this paper bridges two literatures that rarely meet: the New Monetarist tradition following Lagos and Wright (2005), in which the demand for money is derived from explicit frictions in exchange, and the macro-banking framework following Gertler and Karadi (2011), in which banks face an incentive constraint that makes their leverage endogenous. This makes it possible to examine how CBDC competes with deposits as a substitute and, at the same time, how the banking sector responds. The closest predecessor is Assenmacher, Bitter and Ristiniemi (2023), who combine a New Monetarist decentralized market with a New Keynesian model with financial frictions. This paper

differs from theirs in two respects. First, prices are flexible here and sticky in their model. Second, bank runs are endogenous here, so that financial fragility has two margins: illiquidity and insolvency.

1.1 Related literature

This paper also contributes to a growing literature on CBDC, which falls into three broad categories: financial disintermediation, financial stability and design of holding limits.[1]

On financial intermediation, earlier literature such as Brunnermeier and Niepelt (2019) found that CBDC issuance is essentially neutral for both bank funding and economic allocations if central bank actively recycle funds back into the banking sector. This paper departs away from these literature since the substitution from CBDC drives down the liquidity premium of deposits, which genuinely increases of the cost of intermediation, instead of just being a relabeling of bank liabilities. It's also worth mentioning that Barrdear and Kumhof (2022) tested the design where CBDC is issued against government debt, and found that issuing 30% GDP worth of CBDC would raise the steady state output level by 3%. And there have also been literature that measures the magnitudes of the departure. Whited, Wu and Xiao (2023) estimated that a dollar of CBDC replaces about eighty cents of deposits, and Adalid et al. (2022) put euro-area deposit substitution at €647 billion under a €3,000 limit. Another margin is to examine instances where CBDC might actually contribute to financial intermediation. Some literature (Andolfatto 2021; Chiu et al. 2023; Keister and Sanches 2023) have found that if the banking sector is distorted to begin with, the wedge that is in favor of the banking sector might be competed away by the issuance of CBDC, which improves the efficiency even though the costs of raising funds are increased. Since the market distortion channel works in the opposite direction, isolating out the liquidity channel gives an upper bound on the financial disintermediation.

On financial stability, it is often concerned that a CBDC facilitates bank runs as it lowers the cost of fleeing. Bidder, Jackson and Rottner (2025) find that the run probability roughly doubles and imposing a holding limit restores it. Williamson (2022b) reaches the same conclusion in a model as insolvency can trigger panics; Schilling, Fernández-Villaverde and Uhlig (2024) show that a direct intermediation by central bank cannot reach an efficient allocation, price stability and financial stability at once. Fernández-Villaverde et al. (2021) finds that if central bank monopolize deposits can reach the efficient allocation but still inherits the run problem along with the deposits. At the same time, there are also other literature suggesting that the issuance of CBDC actually contribute to financial stability. Keister and Monnet (2022) argues that maturity transformation would be limited, and outflows would allow weak banks to be identified early and policy makers could act on resolving it early on. Closest to this paper are two papers: by Bitter (2025), who also studies bank fragility by placing CBDC in a Gertler–Kiyotaki economy, as store of value, and

[1] Ahnert et al. (2024) and Infante et al. (2024) survey the field.

reached similar results: bank net worth is lowered but the shock required to trigger a bank run is larger. The other is that Assenmacher, Bitter and Ristiniemi (2023) incorporated a Lagos–Wright decentralized market with a New Keynesian centralized market carrying Gertler–Karadi banking sector, but their model does not have a bank run margin and the a single pooled meeting makes CBDC the perfect substitute of bank deposits. This paper is different in the sense that it puts together the New Monetarist framwork with Gertler-Karadi banking sector and carries an endogenous bank run margin, while the differed acceptance of various assets in the decentralized market meeting separates CBDC from deposits. And this paper finds that CBDC lowers the fragility through the bank leverage channel: as leverage ratio drops, liquidation recovery ratio increases because there are fewer claims.

As for holding limits, the literature is thinner and largely institutional. Agur, Ari and Dell'Ariccia (2022) suggests that a quantity limit might help provide a middle ground between CBDC being too close to a substitute for deposits and therefore risking crowding out banks, and being too close to cash-like so that cash disappears. Bindseil (2020) proposed two-tier design to keep a CBDC attractive for being used a means of payment and unattractive as a store of value to avoid crowding out the banking sector. However, the European Central Bank wen the other way by considering adopting a quantity limit of €3,000. Meller and Soons (2023) simulate a launch across more than two thousand euro-area banks and find that a €3,000 limit is entirely manageable. Closest on the welfare question is Burlon, Muñoz and Smets (2024), who finds CBDC provides social welfare gain through the liquidity channel while causes social welfare loss through disintermediation. And a welfare optimal quantity for CBDC is 15 to 45 percent of quarterly GDP, roughly $3,600 to $10,700. Assenmacher et al. (2021) compared three CBDC design and found that uncapped CBDC maximizes welfare and therefore imposing holding cap is welfare-reducing and the only benefit is the containment of disintermediation. Kumhof and Noone (2018) on the other hand explored another CBDC design to reduce bank fragility: CBDC is issued against eligible securities and therefore bank balance sheet would not contract as banks acquiring CBDCs. Also, there is no guaranteed convertibility of deposits into CBDC. They found that if this design was implemented, CBDC issuance would not necessarily lead to disintermediation. However, it is worth mentioning that their conclusion rests on banks replacing deposits outflow with non-deposit liabilities, which is a margin absent in this paper by construction.

Section 2 sets out the model and Section 3 the calibration. Section 4 reports the steady states, Sections 5–8 the four results, and Section 9 concludes.

2 Model

2.1 Environment

Time is discrete. Each period starts with a centralized market (CM) followed by a decentralized market (DM). The CM follows Gertler and Karadi (2011) and features a banking sector with a financial friction. Six types of agents operate in this economy: households, bankers, capital goods producers, intermediate goods producers, final goods producers and the central bank. Preferences in the CM are quasi-linear, which removes wealth effects and keeps the model tractable: the portfolio a household chooses in the CM does not depend on its trading history in the DM, so every household leaves the CM with the same portfolio. Bankers face a moral hazard problem, which gives rise to an incentive constraint that limits their leverage. The DM follows the New Monetarist framework of Lagos and Wright (2005), which microfounds the role of cash, deposits and CBDC as means of payment and therefore captures liquidity premium on each of them. A household enters the DM as a buyer with probability ω and as a seller with the same probability; with the remaining probability $1 - 2\omega$ it does not trade. Meetings in the DM differ in which assets the seller accepts as payment. In each meeting, the buyer pays the seller with the assets carried from the CM that the seller accepts. This allows us to examine how CBDC competes with deposits as a means of payment. The following sections first describe households, banks and firms in the CM, then trade between buyers and sellers in the DM, and finally the central bank and the holding limit on CBDC.

2.2 Household

The household problem

In the CM there is a continuum of identical households. The households are divided into two types: bankers and workers. A fraction $1 - \mathcal{F}$ of the households are workers, and the rest $\mathcal{F}$ are bankers. A banker remains a banker in the following period with probability σ_b. Each period, a measure $(1 - \sigma_b)\,\mathcal{F}$ of bankers exit, return their accumulated net worth to the household and become workers, and an equal measure of workers become bankers, each endowed with w_b. There is perfect consumption insurance within the household, so the household has a single budget constraint and a single discount factor, which its bankers also use.

The household maximizes its value function V_t^{CM} by choosing CM consumption C_t, labor L_t, capital held directly $K_{h,t}$, and a portfolio of real cash m_t, real deposits d_t, and real CBDC e_t:

$$V_t^{CM} \;=\; \max_{C_t,\, L_t,\, m_t,\, d_t,\, e_t,\, K_{h,t}} \Big\{ U(C_t) \;-\; A\, L_t \;-\; \varsigma_t \;+\; \mathbb{E}_t\big[V_t^{DM}\big] \Big\}, \tag{1}$$

with $U(C_t) = \ln C_t$, subject to the budget constraint

$$\begin{aligned} C_t + m_t + d_t + e_t + Q_t K_{h,t} \;&= W_t L_t + T_t + \Upsilon_t \\ &\quad + R_t^m m_{t-1} + R_{t-1}^d d_{t-1} + R_t^e e_{t-1} + R_t^b\, Q_{t-1} K_{h,t-1}, \end{aligned} \tag{2}$$

where W_t is the real wage, T_t the lump-sum transfer from the central bank, and Υ_t the net payout from ownership of firms and from exiting bankers, net of the endowment paid to

entrants. The term ς_t in (1) is the utility cost of managing capital held directly, specified below.

The gross real returns are R_t^m, R_{t-1}^d, R_t^e and R_t^b on cash, deposits, CBDC and capital respectively. The deposit return carries the date $t-1$ because the deposit rate is agreed when the deposit is made and paid one period later. The three liquid assets, cash m_t, deposits d_t and CBDC e_t, are carried into the DM and can be used as payment in the meetings where they are accepted. m_{t-1}, d_{t-1}, and e_{t-1} are the holdings carried over from the previous period. Payments made and received in the DM differ across households but sum to zero, and with quasi-linear preferences they change only hours worked, so they are left out of (2). CM preferences are quasi-linear, $U(C) - AL$ with $U'(C) = 1/C$, so the marginal utility of CM wealth is $\lambda_t = 1/C_t$. The household's stochastic discount factor between t and $t+1$ is

$$\Lambda_{t,t+1} \;\equiv\; \beta\,\frac{\lambda_{t+1}}{\lambda_t} \;=\; \beta\,\frac{C_t}{C_{t+1}}. \tag{3}$$

Households may hold capital directly, but they are less efficient than banks at managing it and bear a management cost. The idea goes back to Gertler and Kiyotaki (2015); the specification here follows Gertler, Kiyotaki and Prestipino (2020), in which the management cost ς_t is a utility cost that is increasing and convex in the share of the capital stock held by households once that share exceeds a threshold γ:

$$\varsigma_t = \begin{cases} \dfrac{\chi}{2}\Big(\dfrac{K_{h,t}}{K_t} - \gamma\Big)^2 K_t & \text{if } K_{h,t}/K_t > \gamma, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

The household takes the aggregate capital stock K_t as given. Below the threshold, holding capital directly is costless; above it, the marginal cost rises linearly with the share. Because the incentive constraint limits how much capital banks can hold, households hold a share above γ in equilibrium, and in a bank run they absorb the entire stock.

The first-order condition for capital held directly is

$$\mathbb{E}_t\big[\Lambda_{t,t+1} R_{t+1}^b\big]\, Q_t \;=\; Q_t + \chi\Big(\frac{K_{h,t}}{K_t} - \gamma\Big) C_t. \tag{5}$$

The cost is in units of utility, so its marginal value is divided by the marginal utility of wealth $\lambda_t = 1/C_t$ to express it in goods; this is where C_t on the right side comes from. Condition (5) is the household's demand for capital: the larger the share households have to hold, the lower the price Q_t they are willing to pay for a given expected return.

The optimality conditions for labor supply and for the three liquid assets are

$$A = W_t \lambda_t, \tag{6}$$

$$\lambda_t = \frac{\partial\, \mathbb{E}_t\big[V_t^{DM}\big]}{\partial a_t} \qquad \text{for } a_t \in \{m_t,\ d_t,\ e_t\}. \tag{7}$$

The left side of (7) is the cost, in units of utility, of carrying one more unit of an asset out of the CM. The right side is the benefit: the value of the asset as a store of value plus, in the meetings where it is accepted, its value as a means of payment. That benefit depends on the structure of the DM, so the three conditions are derived in the subsection on the decentralized market below. For CBDC the condition is also affected by the holding limit, which is a policy choice of the central bank and is introduced with it.

2.3 Banks

The banker's problem

An individual bank intermediates capital $k_{b,t}$ at the price Q_t, funded by raising deposits d_t and its own net worth n_t:

$$Q_t k_{b,t} = d_t + n_t. \tag{8}$$

The net worth a bank carries into period t is the payoff on the assets it bought in $t-1$ less what it repays to depositors, $n_t = R_t^b Q_{t-1} k_{b,t-1} - R_{t-1}^d d_{t-1}$, where R_t^b is the gross real return per unit of value invested in capital, given in (27). Moving this expression one period forward and using the balance sheet (8) to substitute for deposits gives the law of motion of net worth:

$$n_{t+1} = \big(R_{t+1}^b - R_t^d\big) Q_t k_{b,t} + R_t^d n_t, \tag{9}$$

A banker survives into the next period with probability σ_b and otherwise exits, returning the accumulated net worth to the household. Because of perfect consumption insurance within the household, bankers discount future payoffs with the household's stochastic discount factor $\Lambda_{t,t+1}$. The value of being a banker at time t is therefore

$$V_t = \mathbb{E}_t\Big[\Lambda_{t,t+1}\big\{(1-\sigma_b) n_{t+1} + \sigma_b V_{t+1}\big\}\Big]. \tag{10}$$

The incentive constraint

Nothing in (10) by itself bounds the balance sheet: with $R^b > R^d$ the banker would want to issue deposits without limit. Following Gertler and Karadi (2011), what limits the balance sheet is a moral hazard problem: after raising deposits the banker can either operate honestly or divert bank assets for personal use. Operating honestly means that banker holds the assets until they pay off in the next period and then repays depositors. Also, a banker who diverts takes a fraction θ of the assets for his household. Depositors can then force the bank into bankruptcy and recover the remaining fraction $1-\theta$, so a diverting banker gives up the bank and its continuation value V_t. Households therefore deposit only as long as the banker has at least the value of the assets he could divert:

$$V_t \;\geq\; \theta\, Q_t k_{b,t}. \tag{11}$$

Let $\phi_t \equiv Q_t k_{b,t}/n_t$ be the leverage ratio of the bank. The law of motion (9) can then be written as

$$n_{t+1} = \left[\left(R^b_{t+1} - R^d_t\right)\phi_t + R^d_t\right] n_t, \tag{12}$$

Define

$$\mu_t = \mathbb{E}_t\left[\Lambda_{t,t+1}\,\Omega_{t+1}\left(R^b_{t+1} - R^d_t\right)\right], \tag{13}$$

$$\nu_t = \mathbb{E}_t\left[\Lambda_{t,t+1}\,\Omega_{t+1}\right] R^d_t, \tag{14}$$

$$\Omega_{t+1} = 1 - \sigma_b + \sigma_b \frac{V_{t+1}}{n_{t+1}}, \tag{15}$$

where μ_t is the expected discounted excess return on a unit of bank assets over the deposit that funds it, and ν_t is the expected discounted value of a unit of net worth. Both are weighted by Ω_{t+1}, the value to the banker of a unit of net worth at $t+1$: a unit is worth 1 to a banker who exits, which happens with probability $1-\sigma_b$, and V_{t+1}/n_{t+1} to a banker who continues.

Substituting (12), (13) and (14) into (10) and (11), and using the fact that the value of a bank is proportional to its net worth, the banker's problem is to choose the leverage ratio to maximize

$$\frac{V_t}{n_t} = \max_{\phi_t} \left(\mu_t \phi_t + \nu_t\right) \tag{16}$$

subject to the incentive constraint

$$\theta \phi_t \leq \mu_t \phi_t + \nu_t \tag{17}$$

When the constraint binds, the leverage ratio is

$$\phi_t = \frac{\nu_t}{\theta - \mu_t} \tag{18}$$

The constraint binds as long as $0 < \mu_t < \theta$. With $\mu_t > 0$ every additional unit of assets raises the value of the bank, so the banker expands until the constraint stops him; $\mu_t < \theta$ ensures that this happens at a finite leverage ratio. Both inequalities hold in every equilibrium studied below.

A higher R^d_t lowers ϕ_t through two channels that reinforce each other. First, a higher R^d_t narrows the spread $R^b_{t+1} - R^d_t$ in μ_t: the bank earns less on each unit of assets, the denominator of (18) rises, and leverage falls. Second, lower profits in every future period reduce the value of continuing as a banker, which lowers Ω_{t+1} and through it both μ_t and ν_t. The deposit rate also enters ν_t directly, where it works in the opposite direction, but that effect is dominated in every steady state computed below. This is the channel through

which CBDC acts on banks: by compressing the liquidity premium on deposits it raises R^d_t, which shrinks bank balance sheets and at the same time lowers their leverage.

Aggregate net worth

The leverage ratio ϕ_t does not depend on the characteristics of an individual bank, so summing across banks gives

$$Q_t K_{b,t} = \phi_t N_t. \tag{19}$$

where $K_{b,t}$ and N_t are the capital and the net worth of the banking sector. Aggregate deposits are $D_t = Q_t K_{b,t} - N_t$, which in equilibrium equal the deposits held by households.

Aggregate net worth N_t is the net worth of the bankers who survive from the previous period plus the endowment of the new ones,

$$N_t = \sigma_b \Big(R^b_t \, Q_{t-1} K_{b,t-1} - R^d_{t-1} D_{t-1} \Big) + W_b, \tag{20}$$

with $W_b = (1 - \sigma_b)\mathcal{F} w_b$ the *constant* aggregate endowment of entering bankers.[2] Because the deposit rate in (20) was agreed in the previous period, an unexpected fall in the return on assets R^b_t is absorbed entirely by net worth.

2.4 Firms and capital goods

Production involves three types of firms: final goods producers, intermediate goods producers and capital goods producers. Final goods producers are monopolistically competitive; the other two are perfectly competitive.

Final goods producers

A continuum of final goods producers indexed by $f \in [0, 1]$ buys the intermediate good and differentiates it one for one. Final output is the constant-elasticity aggregate of the resulting varieties,

$$Y_t = \left[\int_0^1 Y_t(f)^{\frac{\epsilon-1}{\epsilon}} \, df \right]^{\frac{\epsilon}{\epsilon-1}}, \qquad Y_t(f) = \left(\frac{P_t(f)}{P_t} \right)^{-\epsilon} Y_t, \tag{21}$$

with $\epsilon > 1$ the elasticity of substitution across varieties and $P_t = \big[\int_0^1 P_t(f)^{1-\epsilon} df \big]^{1/(1-\epsilon)}$ the corresponding price index. Producer f buys at the intermediate goods price P^m_t and

[2] Under Gertler–Karadi's own specification the endowment of entering bankers is proportional to assets. Steady-state leverage is then pinned down by the banking parameters alone and cannot respond to CBDC. With a constant endowment the leverage ratio is determined jointly with the rest of the model, as in Bitter (2025).

sells at $P_t(f)$, so it chooses its price to maximize

$$\left(P_t(f) - P_t^m\right) Y_t(f) \tag{22}$$

subject to the demand curve in (21).

Prices are flexible[3], so every producer sets a constant markup over its marginal cost, $P_t(f) = \frac{\epsilon}{\epsilon-1} P_t^m$. All producers then charge the same price and sell the same quantity, $P_t(f) = P_t$ and $Y_t(f) = Y_t$, so the relative price of the intermediate good is

$$\frac{P_t^m}{P_t} = \frac{\epsilon - 1}{\epsilon} \;\equiv\; P_{CM}\,, \tag{23}$$

and final output equals intermediate output, $Y_t = Y_t^m$. Real profits are $(1 - P_{CM})Y_t = Y_t/\epsilon$ and are paid to households, who own the firms, as part of Υ_t in (2).

Since the markup is constant, monopolistic competition lowers the wage and the return on capital through P_{CM} in (26) and (27), and with them the steady-state capital stock, but it plays no role in the dynamics. The monopolistic structure is kept so that the model nests the New Keynesian case: a pricing friction could be added without changing anything else.

Intermediate goods producers

A competitive intermediate goods producer produces with the capital stock installed in the previous period, K_{t-1}, and with labor L_t. The capital stock is the sum of the capital intermediated by banks and the capital held directly by households, $K_t = K_{b,t} + K_{h,t}$. The producer finances its capital by issuing claims at the price Q_{t-1}, which banks and households buy, and it pays the holders of these claims the return R_t^b. Capital is subject to a capital quality shock ξ_t, so the effective capital stock used in production is $\xi_t K_{t-1}$. The production function is standard Cobb-Douglas:

$$Y_t^m = Z_t\left(\xi_t K_{t-1}\right)^{\alpha} L_t^{1-\alpha} \tag{24}$$

where Z_t is total factor productivity and $0 < \alpha < 1$ is the capital share. Productivity and capital quality follow first-order autoregressive processes in logs,

$$\ln\frac{Z_t}{Z} = \rho_Z \ln\frac{Z_{t-1}}{Z} + \sigma_Z \varepsilon_t^Z, \qquad \ln\xi_t = \rho_\xi \ln\xi_{t-1} + \sigma_\xi \varepsilon_t^\xi, \tag{25}$$

[3]The main results of the paper concern how CBDC and a holding limit changes bank funding and leverage. With a nominal rigidity, the results would partly reflect how the limit interacts with that rigidity, and the two effects would be hard to separate quantitatively.

The cost here is that nothing in this paper speaks to stabilization, or to interest-rate pass-through. These questions are the ones that Assenmacher, Bitter and Ristiniemi (2023) and Burlon, Muñoz and Smets (2024) address, and both find a role for CBDC in smoothing the cycle. That CBDC stabilizes in their models while a holding limit is nearly neutral for dynamics here is not a contradiction: in their models the quantity of CBDC adjusts to shocks, whereas a binding holding limit fixes it.

where Z is steady-state productivity, the steady-state value of ξ_t is one, and the innovations ε_t^Z and ε_t^ξ are independent with unit variance.

The intermediate goods producer sells the intermediate goods to the final goods sector at the relative price P_{CM}. Its capital was installed in the previous period, so in period t it chooses labor to maximize revenue less the wage bill, plus the resale value of the undepreciated capital, less the payment to the holders of its claims:

$$\max_{L_t} P_{CM}\, Y_t^m \;-\; W_t L_t \;+\; (1-\delta)\,\xi_t Q_t K_{t-1} \;-\; R_t^b\, Q_{t-1} K_{t-1}.$$

The first-order condition for labor is

$$W_t = (1-\alpha)\, P_{CM}\, \frac{Y_t^m}{L_t}, \tag{26}$$

The wage equals the marginal product of labor valued at the relative price of the intermediate good. The producer is competitive and has no net worth of its own, so it earns zero profit in every state and pays everything that is left after wages to the holders of its claims. The return per unit of value invested is therefore

$$R_t^b \;= \xi_t\, \frac{\alpha\, P_{CM}\, Y_t^m / (\xi_t K_{t-1}) + (1-\delta) Q_t}{Q_{t-1}}, \tag{27}$$

The numerator, multiplied by ξ_t, is what a unit of capital bought in $t-1$ delivers in t: the rental income it generates plus the resale value of what is left after depreciation. Dividing by Q_{t-1} expresses it per unit of value invested, which is why the payoff of a bank is written $R_t^b Q_{t-1} k_{b,t-1}$ in Section 2.3. Capital quality affects both parts, but almost all of the payoff is the undepreciated stock, so a fall in ξ_t acts mainly as a writedown of the value of existing capital. This is why it is the natural shock for studying bank balance sheets.

Capital goods producers

Competitive capital goods producers use a technology that converts final goods into capital goods one for one, and sell the capital goods at Q_t. They face an adjustment cost that increases with the rate at which investment changes from one period to the next. The cost makes the supply of new capital less than perfectly elastic, so the price of capital Q_t moves with investment.

Net investment is gross investment less the depreciation of the effective capital stock,

$$\mathcal{I}_t \equiv I_t - \delta\, \xi_t K_{t-1}, \tag{28}$$

and the capital stock evolves according to

$$K_t = \xi_t K_{t-1} + \mathcal{I}_t = (1-\delta)\, \xi_t K_{t-1} + I_t, \tag{29}$$

Let $g_t \equiv \frac{\mathcal{I}_t + I^{ss}}{\mathcal{I}_{t-1} + I^{ss}}$ denote the growth rate of investment, where $I^{ss} = \delta K$ is steady-state gross investment. Net investment is zero in the steady state, so the growth rate is defined on net investment plus I^{ss}, which makes $g = 1$ there. I^{ss} is the steady-state investment of the economy under consideration, so it takes a different value under each holding limit. Capital goods producers are owned by households and discount with $\Lambda_{t,t+1}$. Each chooses I_t to maximize the present value of revenue less the cost of inputs and of adjustment,

$$\mathbb{E}_t \sum_{s \geq 0} \Lambda_{t,t+s} \Big[Q_{t+s} I_{t+s} - I_{t+s} - \tfrac{\eta_i}{2} (g_{t+s} - 1)^2 \big(\mathcal{I}_{t+s} + I^{ss} \big) \Big], \tag{30}$$

where $\Lambda_{t,t+s} = \beta^s C_t / C_{t+s}$ is the discount factor between t and $t+s$. The first-order condition is

$$Q_t = 1 + \frac{\eta_i}{2}(g_t - 1)^2 + \eta_i (g_t - 1) g_t - \mathbb{E}_t \Big[\Lambda_{t,t+1}\, \eta_i (g_{t+1} - 1) g_{t+1}^2 \Big]. \tag{31}$$

On the right side, the 1 is the unit of final goods converted into a unit of capital, the second term is the adjustment cost incurred per unit of investment, the third is the marginal cost of raising investment today, and the last term, which is subtracted, is the saving on the adjustment cost of the next period from starting at a higher level of investment. In the steady state $g = 1$, so $Q = 1$ and profits are zero; outside the steady state profits are paid to households. The parameter η_i governs how strongly the price of capital responds to shocks, and therefore how much bank net worth is revalued. With $\eta_i = 0$ the price of capital is $Q_t \equiv 1$ and capital is supplied perfectly elastically: shocks are absorbed by the quantity of capital, and bank net worth is not revalued through the price of capital.

2.5 Decentralized market

After the CM closes, each household enters the DM. With probability ω it is a buyer, who wants to consume a good that only sellers can produce; with probability ω it is a seller; otherwise it does not trade. A buyer who consumes q units of the DM good obtains utility $u(q) = \psi \ln q$, and a seller who produces q units bears the cost $c(q) = s\, q^{1/s}$, with $\psi > 0$ and $0 < s < 1$, as in Assenmacher, Bitter and Ristiniemi (2023). Buyers and sellers are anonymous and cannot commit to future payments, so sellers do not extend credit and a buyer has to pay with assets carried from the CM.

Meetings differ in the assets the seller accepts. A buyer is assigned to one of three types of meeting: with probability k_M to a meeting in which only cash is accepted (type M), with probability k_E to one in which only CBDC is accepted (type E), and with probability k_{DE} to one in which both deposits and CBDC are accepted (type DE), where $k_M + k_E + k_{DE} = 1$. There is no meeting in which deposits are accepted and CBDC is not: a seller who can take a payment from a bank account can also take one from a CBDC account. Type E meetings represent transactions in which CBDC can be used and a card

payment cannot. One good example is a payment made without a network connection: the proposed regulation for the digital euro requires that it be usable offline, between two devices, whereas a payment from a bank account has to reach the bank. Such transactions are a small share of the total, and they are what gives CBDC a use that deposits do not have.The household chooses its portfolio in the CM before it knows its role and its meeting type.

The assets a buyer can use in a meeting of each type, measured in units of the CM good of period $t+1$, are

$$A_{M,t+1} = R^m_{t+1} m_t, \qquad A_{E,t+1} = R^e_{t+1} e_t, \qquad A_{DE,t+1} = R^d_t d_t + R^e_{t+1} e_t. \tag{32}$$

In a type DE meeting deposits and CBDC add up: a unit of value held as CBDC buys exactly what a unit of value held as deposits buys, so the two are perfect substitutes there.

Each type of meeting is a competitive market: buyers and sellers take the price $p_{j,t}$ of the DM good, expressed in units of the CM good of period $t+1$, as given, for $j \in \{M, E, DE\}$. A unit of the CM good received in $t+1$ is worth $\beta\lambda_{t+1}$ in utility of period t. A seller therefore produces up to the point where $c'(q_{j,t}) = \beta\lambda_{t+1} p_{j,t}$. A buyer chooses $q_{j,t}$ to maximize $u(q_{j,t}) - \beta\lambda_{t+1} p_{j,t} q_{j,t}$ subject to the payment constraint $p_{j,t} q_{j,t} \leq A_{j,t+1}$.

If the buyer holds enough assets, the constraint is slack and the quantity traded is the efficient one, q^*, at which $u'(q^*) = c'(q^*)$. Otherwise the buyer spends all the assets the seller accepts, $p_{j,t} q_{j,t} = A_{j,t+1}$, and together with the condition of the seller this gives $q_{j,t} c'(q_{j,t}) = \beta\lambda_{t+1} A_{j,t+1}$, or

$$q_{j,t} = \big(\beta\lambda_{t+1} A_{j,t+1}\big)^s. \tag{33}$$

The liquidity premium in a type j meeting is the gap between the marginal utility of the buyer and the marginal cost of the seller,

$$LP_{j,t+1} \equiv \frac{u'(q_{j,t})}{c'(q_{j,t})} - 1 = \frac{\psi}{\beta\lambda_{t+1} A_{j,t+1}} - 1. \tag{34}$$

It is positive when the buyer is constrained and falls to zero when $A_{j,t+1}$ reaches $\psi/(\beta\lambda_{t+1})$, the value of assets at which the meeting is satiated. In a constrained meeting an additional unit of assets is worth $1 + \mathrm{LP}_{j,t+1}$ times what it is worth as a store of value, because it relaxes the payment constraint.

The marginal value of each asset in (7) can now be written out. A unit of an asset is worth its return as a store of value in every state. In addition it earns the liquidity premium of every type of meeting in which it is accepted, with the probability ωk_j that the household is a buyer in a meeting of that type. The conditions for cash and deposits are

$$1 = \mathbb{E}_t\Big[\Lambda_{t,t+1} R^m_{t+1}\big(1 + k_M\, \omega\, LP_{M,t+1}\big)\Big], \tag{35}$$

$$1 = \mathbb{E}_t\Big[\Lambda_{t,t+1} R^d_t\big(1 + k_{DE}\, \omega\, LP_{DE,t+1}\big)\Big], \tag{36}$$

and, when the amount of CBDC a household may hold is not limited, the condition for CBDC is

$$1 = \mathbb{E}_t\Big[\Lambda_{t,t+1} R^e_{t+1}\big(1 + k_E\,\omega\,LP_{E,t+1} + k_{DE}\,\omega\,LP_{DE,t+1}\big)\Big]. \tag{37}$$

Three features of these conditions drive the results of the paper. First, an asset pays less than the rate of time preference to the extent that it is useful in payments. In a steady state (36) gives $R^d = 1/[\beta(1 + k_{DE}\,\omega\,LP_{DE})]$, so the deposit rate is below $1/\beta$ as long as $LP_{DE} > 0$. This is the source of the cheap funding of banks. Second, deposits are used only in type DE meetings, so the deposit rate is governed by LP_{DE} alone, and LP_{DE} depends on the sum of deposits and CBDC in (32). Every unit of CBDC that households hold therefore lowers LP_{DE} and raises the rate banks have to pay on deposits. Third, CBDC earns the premium of two types of meeting. In type DE meetings it is a perfect substitute for deposits. Type E meetings give it a use that deposits do not have, which is why households can want to hold CBDC even when it pays less than deposits.

2.6 Central bank, the holding limit and market clearing

The central bank issues cash and CBDC and has three instruments: the growth rate of the nominal stock of cash, the nominal interest rate on CBDC, and a limit on the amount of CBDC a household may hold. Prices are flexible, so there is no interest rate rule; the nominal side of the economy is determined by money growth. The nominal stock of cash grows at the constant rate g_m. Households demand real cash balances m_t according to (35), and the price level adjusts so that the two are consistent. With π_t the inflation rate between $t-1$ and t,

$$1 + \pi_t = (1 + g_m)\,\frac{m_{t-1}}{m_t}, \tag{38}$$

so inflation equals g_m in a steady state. Cash pays no interest, and CBDC pays a gross nominal interest rate $\bar{\imath}^{\,e}$ that the central bank keeps constant. Their real returns are

$$R^m_t = \frac{1}{1 + \pi_t}, \qquad R^e_t = \frac{\bar{\imath}^{\,e}}{1 + \pi_t}. \tag{39}$$

The rate on CBDC is set so that CBDC pays less than deposits in every steady state considered. CBDC therefore does not compete with deposits by offering a higher return: whatever it takes from deposits, it takes as a means of payment.

The third instrument is the holding limit. A household may hold at most $\bar{e}$ units of CBDC, where the limit is specified in real terms:

$$e_t \le \bar{e}. \tag{40}$$

Let ζ_t be the multiplier on (40), divided by the marginal utility of wealth λ_t so that it is

measured in goods. With the limit, the condition for CBDC (37) becomes

$$1+\zeta_t = \mathbb{E}_t\Big[\Lambda_{t,t+1} R^e_{t+1}\big(1+k_E\,\omega\,LP_{E,t+1}+k_{DE}\,\omega\,LP_{DE,t+1}\big)\Big], \qquad \zeta_t \geq 0, \qquad \zeta_t\,(\bar{e}-e_t) = 0. \tag{41}$$

When the limit binds, $e_t = \bar{e}$ and (41) determines ζ_t, the value to a household of being allowed to hold one more unit of CBDC. When it does not bind, $\zeta_t = 0$ and (41) determines the amount of CBDC households choose to hold.

Why households want more CBDC than the limit allows can be read from a steady state. Combining (41) with the condition for deposits (36) gives

$$\zeta = \frac{R^e}{R^d} - 1 + \beta R^e\,k_E\,\omega\,LP_E. \tag{42}$$

The first two terms sum to a negative number, because CBDC pays less than deposits: in type DE meetings the two are perfect substitutes, so on that margin alone a household would rather hold deposits. The last term is the liquidity premium that CBDC earns in type E meetings. The limit therefore binds only because of the meetings in which deposits are not accepted, and it binds more tightly the lower $\bar{e}$ is, because LP_E rises as CBDC becomes scarcer. As the limit is raised, the first thing that happens is that type DE meetings become satiated: $LP_{DE} = 0$ and $R^d = 1/\beta$, so deposits lose their liquidity premium entirely. Beyond that point more CBDC no longer affects banks, although the limit continues to bind for households until LP_E has fallen far enough to bring ζ to zero.

The central bank holds no assets and passes its net revenue to households as a lump-sum transfer,

$$T_t = \big(m_t - R^m_t m_{t-1}\big) + \big(e_t - R^e_t e_{t-1}\big). \tag{43}$$

The first term is the revenue from issuing cash. The second is new issuance of CBDC less the interest paid on the outstanding stock. Under a binding limit it equals $-(R^e_t - 1)\bar{e}$, which is negative when CBDC pays a positive real return, so T_t can be negative, in which case it is a lump-sum tax. The funds that households move from deposits into CBDC are not lent back to banks. Brunnermeier and Niepelt (2019) show that if the central bank passes these funds through to banks, the introduction of CBDC leaves bank funding unchanged. The results below are conditional on the central bank not doing so.

The markets for labor, capital and deposits clear, with $K_t = K_{b,t} + K_{h,t}$ and $D_t = d_t$, and so does the market for final goods:

$$Y_t = C_t + I_t + \frac{\eta_i}{2}(g_t - 1)^2(\mathcal{I}_t + I^{ss}). \tag{44}$$

Final output is used for consumption, investment and the adjustment cost of investment. The transfer T_t does not appear because it only moves resources between the central bank and households. The management cost ς_t does not appear because it is a cost in utility and uses no goods. The DM good is produced and consumed within the DM and is not part of Y_t.

2.7 Measures of Fragility

Bank fragility is measured in two ways. The first measure is based on solvency. A bank is solvent in period t if the payoff on its assets covers what it owes to depositors, $R^b_t Q_{t-1} k_{b,t-1} \geq R^d_{t-1} d_{t-1}$. Dividing by assets and using the leverage ratio, this holds when the realized return on assets is at least $R^d_{t-1}(1 - 1/\phi_{t-1})$, the return at which net worth is exactly wiped out. The solvency buffer is the distance between the realized return and this break-even return,

$$BUF_t = R^b_t - R^d_{t-1}\Big(1 - \frac{1}{\phi_{t-1}}\Big), \qquad p_t = \Phi(-BUF_t/\sigma_w)\,. \tag{45}$$

In the model every bank earns the same return R^b_t and the buffer is positive on every path considered, so no bank becomes insolvent. To put the buffer on a scale that is easy to compare across holding limits, the second expression in (45) converts it into the share of banks that would be insolvent if the returns of individual banks differed from R^b_t by a normally distributed component with standard deviation σ_w, where Φ is the standard normal distribution function. The construction follows Mendicino et al. (2020), in whose model the return of each bank carries an idiosyncratic shock and a bank fails when the payoff on its assets falls short of its deposits. There the shock is part of the model; here it is used only to report the buffer. The dispersion σ_w is set so that p matches the average failure rate of US commercial banks, 1.02 percent per year, in the steady state without CBDC; Section 3 gives the details.

Three properties of this measure matter for reading the results. First, in a steady state $BUF = (R^b - R^d) + R^d/\phi$, and the second term is by far the larger: the buffer is essentially equity per unit of assets, the inverse of leverage. Whatever lowers leverage raises the buffer. Second, R^d_{t-1} and ϕ_{t-1} are predetermined, so on impact a shock moves the buffer one for one with the realized return on assets. Third, p_t is a statistic and not an equilibrium probability of failure: the dispersion of returns is not part of the model, and depositors do not price the risk of insolvency. Because p_t is a probability in the tail of a distribution, it magnifies differences, and by how much depends on the distribution that is assumed. At the calibrated anchor, a buffer 4 percent wider lowers p by 30 percent with the normal distribution and by 19 percent with a Laplace distribution, which has fatter tails. The results are therefore stated in terms of the buffer and of the net worth of banks relative to their assets, and p is reported only to give a sense of scale. The second measure is the recovery ratio in a bank run, which Section 2.8 defines. It does not rely on an assumed dispersion.

2.8 Bank runs

Bank runs are modeled as in Gertler and Kiyotaki (2015). A run is a situation in which all households stop rolling over their deposits at the same time. Banks then have to sell their

capital to households, who end up holding the entire stock, $K_{h,t}/K_t = 1$, and are willing to do so only at a price low enough to compensate them for the management cost. Let Q_t^* denote this liquidation price. It follows from the condition of households for capital (5) evaluated at a share of one:

$$Q_t^* = \mathbb{E}_t\Big[\Lambda_{t,t+1}\,\xi_{t+1}\Big(\alpha\,P_{CM}\,\frac{Y_{t+1}^m}{\xi_{t+1}K_t} + (1-\delta)Q_{t+1}\Big)\Big] - \chi(1-\gamma)C_t. \tag{46}$$

The first term is the discounted payoff of a unit of capital, and the second is the marginal management cost when households hold everything. The liquidation price is below the market price Q_t for two reasons: the management cost is at its highest, and Q_{t+1} is the price that prevails while the banking system is being rebuilt after the run.

In the period of a run banks hold no capital and have no deposits, and the net worth of the bankers who were active is lost. Banking resumes in the following period with the endowments of the bankers who entered in the meantime, $(1+\sigma_b)W_b$, and net worth is then rebuilt out of retained earnings as in (20). While banks are small, households hold most of the capital stock and the price of capital is below its steady-state value. This recovery path determines Q_{t+1} in (46), and through it the liquidation price.

A run can occur only if it leaves banks unable to repay. If banks could pay depositors in full even at the liquidation price, no household would have a reason to withdraw. Let R_t^{b*} denote the return on bank assets (27) evaluated at Q_t^* in place of Q_t. The recovery ratio is the liquidation value of bank assets relative to what banks owe,

$$x_t = \frac{R_t^{b*}\,Q_{t-1}K_{b,t-1}}{R_{t-1}^d D_{t-1}} = \frac{R_t^{b*}}{R_{t-1}^d}\,\frac{\phi_{t-1}}{\phi_{t-1}-1}, \tag{47}$$

and a run equilibrium exists in period t if and only if $x_t < 1$. Rearranging, $x_t \geq 1$ is equivalent to $R_t^{b*} \geq R_{t-1}^d(1-1/\phi_{t-1})$, which is the solvency condition behind (45) with the liquidation price in place of the market price. The two measures therefore ask the same question at two different prices: whether banks can repay when their assets are valued at the market price, which is insolvency, and whether they can repay when their assets have to be sold to households, which is illiquidity. Lower leverage improves both.

When $x_{t+1} < 1$, the equilibrium with a run and the equilibrium without one both exist, and which of them occurs is not determined by fundamentals. Following Gertler and Kiyotaki (2015), the probability that households assign in period t to a run in period $t+1$ is higher the less depositors would recover,

$$p_t^{\text{run}} = \max\big\{1 - \mathbb{E}_t\,x_{t+1},\ 0\big\}. \tag{48}$$

The run probability is zero whenever banks could repay in full at the liquidation price. It is written p_t^{run} to keep it apart from the statistic p_t in (45): p_t is computed from the solution and affects nothing, while p_t^{run} is known to households and bankers and enters their decisions.

Runs are anticipated. In a run in period $t+1$, capital is worth the liquidation price, depositors receive the fraction x_{t+1} of what they are owed, deposits can no longer be used in the decentralized market, and bankers lose their net worth. The conditions of households for capital (5) and for deposits (36) therefore have two branches,

$$Q_t + \chi\Big(\frac{K_{h,t}}{K_t} - \gamma\Big)C_t = \mathbb{E}_t\Big[(1 - p_t^{\text{run}})\,\Lambda_{t,t+1}R_{t+1}^{b} + p_t^{\text{run}}\,\Lambda_{t,t+1}^{*}R_{t+1}^{b*}\Big]Q_t, \tag{49}$$

$$1 = \mathbb{E}_t\Big[(1 - p_t^{\text{run}})\,\Lambda_{t,t+1}R_t^{d}\big(1 + k_{DE}\,\omega\,LP_{DE,t+1}\big) + p_t^{\text{run}}\,\Lambda_{t,t+1}^{*}\,x_{t+1}R_t^{d}\Big], \tag{50}$$

where $\Lambda_{t,t+1}^{*}$ is the discount factor of households between period t and a run in period $t+1$. A banker receives the value in (10) only if there is no run, so μ_t and ν_t in (13) and (14) are multiplied by $1 - p_t^{\text{run}}$, and the leverage ratio (18) becomes

$$\phi_t = \frac{(1 - p_t^{\text{run}})\,\nu_t}{\theta - (1 - p_t^{\text{run}})\,\mu_t}. \tag{51}$$

A higher run probability raises the deposit rate that households require and lowers the leverage that the incentive constraint allows. Leverage in turn determines the recovery ratio in (47), so the run probability and the balance sheets of banks are determined together.

When $x_{t+1} \geq 1$ the run probability is zero and (49), (50) and (51) reduce to (5), (36) and (18). Section 4 shows that this is the case in every steady state considered, with and without CBDC. The steady states and the impulse responses below are therefore computed from the conditions without the run terms, which is valid as long as the recovery ratio stays above one along the path. Section 8 solves the model with the run terms and asks how large a shock has to be to bring the recovery ratio below one, so that a run becomes possible, and how the holding limit changes that threshold. That calculation holds output and the capital stock fixed, as in Gertler and Kiyotaki (2015).

For that calculation the model with runs is solved in two steps, as in Gertler and Kiyotaki (2015), which are repeated until the liquidation price no longer changes. Given a liquidation price, the first step finds the steady state of the model with the run terms, from (20), (49) and (51). The second step finds the path that leads back to this steady state after a run, starting from the period in which households hold the whole capital stock and banks have no deposits. The liquidation price is then updated from (46) along that path. Because output and the capital stock are held fixed, a run changes who holds the capital and at what price, and not how much capital there is; a shock enters through the rental rate of capital. The procedure was checked on the model of Gertler and Kiyotaki (2015) itself, where it reproduces their liquidation price to seven digits.

3 Calibration

The model is calibrated to the United States at a quarterly frequency. The parameters fall into three groups: parameters taken from the literature, parameters chosen so that the steady state of the economy without CBDC matches seven targets, and policy parameters. The economy without CBDC is the one that is observed, so every target is imposed on it. The economies with CBDC are then solved with all parameters held fixed, so that differences across holding limits come from the limit alone.

3.1 Parameters taken from the literature

Table 1 lists the parameters that are set outside the model. The preference and technology parameters and the investment adjustment cost are those of Gertler and Karadi (2011), who use an elasticity of substitution of 4.167. The survival probability of bankers follows Gertler and Kiyotaki (2015) and the slope of the management cost follows Gertler, Kiyotaki and Prestipino (2020). The two parameters of the decentralized market, the probability of being a buyer and the curvature of the cost function, are taken from Assenmacher, Bitter and Ristiniemi (2023), whose functional forms are the ones used here; the curvature parameter affects only the quantities traded in the DM and none of the results reported below. The share of CBDC-only meetings cannot be identified from an economy without CBDC and is set to $k_E = 0.015$; its role is discussed with the holding limits below. The persistence of the capital quality shock is the value in Gertler and Karadi (2011), and both shocks have a standard deviation of one percent so that their effects can be compared directly.

Table 1: Parameters set outside the model

Parameter		Value	Source
Discount factor	β	0.99	Gertler and Karadi (2011)
Capital share	α	0.33	Gertler and Karadi (2011)
Elasticity of substitution	ϵ	4.16	Gertler and Karadi (2011)
Investment adjustment cost	η_i	1.728	Gertler and Karadi (2011)
Survival probability of bankers	σ_b	0.95	Gertler and Kiyotaki (2015)
Slope of the management cost	χ	0.105	Gertler, Kiyotaki and Prestipino (2020)
Probability of being a buyer	ω	0.295	Assenmacher, Bitter and Ristiniemi (2023)
Curvature of the cost of DM goods	s	0.68	Assenmacher, Bitter and Ristiniemi (2023)
Share of CBDC-only meetings	k_E	0.015	assumed
Persistence of productivity	ρ_Z	0.95	standard
Persistence of capital quality	ρ_ξ	0.66	Gertler and Karadi (2011)
Standard deviation of the shocks	$\sigma_Z,\ \sigma_\xi$	0.01	normalization
Steady-state productivity	Z	1.25	normalization

3.2 Targets

Seven parameters are chosen so that the steady state without CBDC matches the seven targets in Table 2. The parameters are the share of assets a banker can divert θ, the endowment of new bankers W_b, the utility weight of the DM good ψ, the depreciation rate δ, the threshold of the management cost γ, the share of cash-only meetings k_M and the disutility of labor A. The system is exactly identified, and the table pairs each target with the parameter that is most closely tied to it. Leverage of 6 lies between the values of 4 in Gertler and Karadi (2011) and 10 in Gertler and Kiyotaki (2015). The return on capital is targeted relative to the rate of time preference $1/\beta$ and not relative to the deposit rate. In Gertler and Karadi (2011) the two coincide, but here deposits carry a liquidity premium, so $R^d < 1/\beta$; together the two targets imply a spread between the return on bank assets and the deposit rate of 251 basis points per year. The ratios of deposits and of cash to output are those of the United States in 2026: deposits of \$19.8 trillion against output of \$33.0 trillion, and currency in circulation of \$2.4 trillion, of which 55 percent is taken to be held domestically.

Table 2: Calibration targets and the parameters they determine

Target (economy without CBDC)	Value	Parameter	Value
Bank leverage, ϕ	6.00	θ	0.475
Return on capital, $R^b - 1/\beta$	1.0% per year	W_b	0.0057
Liquidity premium on deposits, $1/(\beta R^d) - 1$	1.5% per year	ψ	2.767
Capital to annual output, $K/4Y$	2.50	δ	0.0125
Deposits to annual output, $d/4Y$	0.600	γ	0.693
Cash to annual output, $m/4Y$	0.040	k_M	0.0036
Hours worked, L	0.33	A	1.762

Three implications of these targets are not targeted themselves. First, the share of capital intermediated by banks is 0.288, because deposits, leverage and the capital stock are tied together by $d/4Y = (1 - 1/\phi)(K_b/K)(K/4Y)$. This is below the 0.33 of Gertler, Kiyotaki and Prestipino (2020). Second, the threshold of the management cost is $\gamma = 0.693$, against 0.61 in Gertler, Kiyotaki and Prestipino (2020): households hold 71 percent of the capital stock in the steady state, just above the threshold. Third, deposits and CBDC are accepted in $k_{DE} = 1 - k_M - k_E = 0.981$ of meetings. The real return on deposits is 2.5 percent per year and the return on capital 5.0 percent. The dispersion $\sigma_w = 0.0622$ in the solvency measure (45) is set so that p equals 0.256 percent per quarter without CBDC, which is 1.02 percent per year. This is the average annual failure rate of US commercial banks between 1984 and 2007, which Corbae and D'Erasmo (2019) target in their calibration.

3.3 Policy parameters and the holding limits

Nominal cash grows at $g_m = 0.005$ per quarter, so steady-state inflation is 2 percent per year. CBDC pays a gross nominal rate of $\bar{\imath}^e = 1.0075$, 3 percent per year, which is a real return of 1 percent per year. This is below the real return on deposits of 2.5 percent in the economy without CBDC, and it stays below the return on deposits under every holding limit.

The holding limit $\bar{e}$ is a real quantity. It is expressed as a fraction κ of annual output in the economy without CBDC, $\bar{e} = \kappa \cdot 4Y$, and converted into dollars per person with nominal output per person of \$95,005 in the second quarter of 2026. Table 3 reports the four limits used below. There is no proposal for a CBDC or for a holding limit in the United States, so the grid is illustrative. Its lower end corresponds to the range that has been analyzed for the digital euro, and its upper end is close to the point at which the liquidity premium on deposits disappears. In the calibrated model type DE meetings are satiated at a limit of \$13,164 per person, and without any limit households would hold \$20,052. All four limits therefore bind, and all four leave deposits with a positive liquidity premium. How much

CBDC households want depends on the share of CBDC-only meetings through (42): with a sufficiently small k_E the highest limits would no longer bind. The third column of the table is the unit in which Burlon, Muñoz and Smets (2024) report their welfare-maximizing quantity of CBDC, 15 to 45 percent of quarterly output, which corresponds to \$3,600 to \$10,700 per person here.

Table 3: Holding limits

Limit per person	κ	Percent of quarterly output	Aggregate
\$1,000	0.0105	4.2	\$0.35 trillion
\$3,000	0.0316	12.6	\$1.04 trillion
\$6,000	0.0632	25.3	\$2.08 trillion
\$12,000	0.1263	50.5	\$4.17 trillion

4 Steady states

This section compares six steady states: the economy without CBDC, the economies with the four holding limits of Table 3, and an economy in which CBDC is issued without a limit. All parameters are those of Section 3, so the steady states differ only because of the limit. Table 4 reports them, and Figure 1 shows the main variables for every limit between zero and \$16,000 per person.[4]

[4]Each steady state solves a system of fourteen equations in fourteen unknowns, with a largest residual below 10^{-13}. Around each of the five steady states that are used for the impulse responses, the number of unstable eigenvalues equals the number of forward-looking variables, seven without CBDC and eight with it, so the equilibrium is locally unique.

Table 4: Steady states

	No CBDC	\$1,000	\$3,000	\$6,000	\$12,000	No limit
CBDC, percent of annual output	0.00	1.05	3.16	6.32	12.63	21.11
Deposits to annual output	0.600	0.591	0.571	0.542	0.480	0.467
Premium on deposits, basis points	150	141	121	89	16	0
Deposit rate, percent per year	2.53	2.63	2.82	3.14	3.88	4.04
Return on capital, percent per year	5.04	5.13	5.31	5.60	6.25	6.39
Bank leverage, ϕ	6.00	5.96	5.88	5.76	5.48	5.43
Bank share of capital	0.288	0.286	0.283	0.277	0.263	0.260
Solvency buffer, BUF	0.1740	0.1751	0.1774	0.1811	0.1900	0.1920
p, percent per quarter	0.256	0.242	0.216	0.179	0.112	0.100
Liquidation price, Q^*	0.9244	0.9246	0.9252	0.9259	0.9275	–
Recovery ratio, x	1.1184	1.1201	1.1238	1.1296	1.1434	–
Change from no CBDC, percent						
Deposits	–	−2.1	−6.4	−12.7	−25.6	−28.1
Deposits to output	–	−1.6	−4.8	−9.7	−20.1	−22.2
Bank net worth	–	−1.4	−4.1	−8.3	−17.0	−18.8
Capital	–	−1.4	−4.2	−8.4	−16.9	−18.6
Output	–	−0.5	−1.7	−3.3	−6.9	−7.6
Consumption	–	−0.4	−1.3	−2.6	−5.5	−6.0

Under each of the four limits households hold exactly the limit. The multiplier ζ on the limit in (41) is positive in all four economies. It falls from 0.245 at \$1,000 to 0.009 at \$12,000, as the limit approaches the amount that households would hold by choice. The liquidity premia of all three types of meetings are positive in every economy with a limit, so cash, CBDC and deposits are all scarce as means of payment.

CBDC makes deposits more expensive for banks. Deposits and CBDC are used in the same meetings, so the CBDC that households hold lowers the liquidity premium on deposits, and households require a higher deposit rate. With a limit of \$6,000 the premium falls from 150 to 89 basis points per year, and the real deposit rate rises from 2.53 to 3.14 percent. A higher cost of deposits lowers the value of a bank to its banker, so the incentive constraint (11) allows less leverage: 5.76 instead of 6.00. Bank net worth is 8.3 percent lower, and deposits fall by 12.7 percent.

Banks hold a smaller share of the capital stock, 27.7 percent instead of 28.8, and households a larger one. Because the management cost (4) increases with the share that households hold, the return that capital has to earn rises from 5.04 to 5.60 percent per year, and the capital stock is 8.4 percent lower. Output falls by 3.3 percent and consumption by 2.6 percent. These effects are close to proportional to the limit: at \$12,000, deposits

fall by 25.6 percent, capital by 16.9 percent and consumption by 5.5 percent. Section 5 examines the mechanism step by step.

The fall in deposits can be measured in two ways, and the two differ because output falls as well. In levels, deposits are 12.7 percent lower at \$6,000; relative to output, they are 9.7 percent lower. The level is the relevant measure for the funding that banks lose, and the ratio is the one that can be compared across economies of different size. Table 4 reports both, and the text says which one is meant wherever the difference matters.

The last column of Table 4 is the economy without a limit. Households then hold CBDC worth \$20,052 per person, 21 percent of annual output. The effect of CBDC on banks ends before that amount is reached. At \$13,164 per person the meetings that accept deposits and CBDC are satiated: the liquidity premium on deposits is zero, and the deposit rate equals the rate of time preference, 4.04 percent per year. CBDC beyond that amount is held only for the meetings that accept nothing else. It does not affect banks, capital or output, which is why every line in Figure 1 is flat to the right of the dotted line. The last column is therefore the largest effect that CBDC can have in this model: deposits are 28.1 percent lower, capital 18.6 percent and consumption 6.0 percent, and leverage is 5.43. A limit of \$12,000 produces about nine tenths of this effect.

Both measures of fragility of Section 2.7 improve as the limit rises. Lower leverage means more net worth for each unit of assets. Banks hold 17.4 cents of net worth for each dollar of assets at \$6,000, against 16.7 without CBDC, and the solvency buffer rises from 0.174 to 0.181. The recovery ratio is above one in every steady state for which it is computed, 1.118 without CBDC and 1.130 at \$6,000.[5] Households would take over the capital of banks at a price between 7 and 8 percent below the market price, and at that price banks could still repay their deposits in full. The run probability (48) is therefore zero, and none of these steady states has runs. Section 6 and Section 8 return to the two measures.

[5]The recovery ratio is not reported for the economy without a limit. The calculation of the liquidation price holds the stock of CBDC fixed during the recovery from a run, which is appropriate when a limit binds and not otherwise.

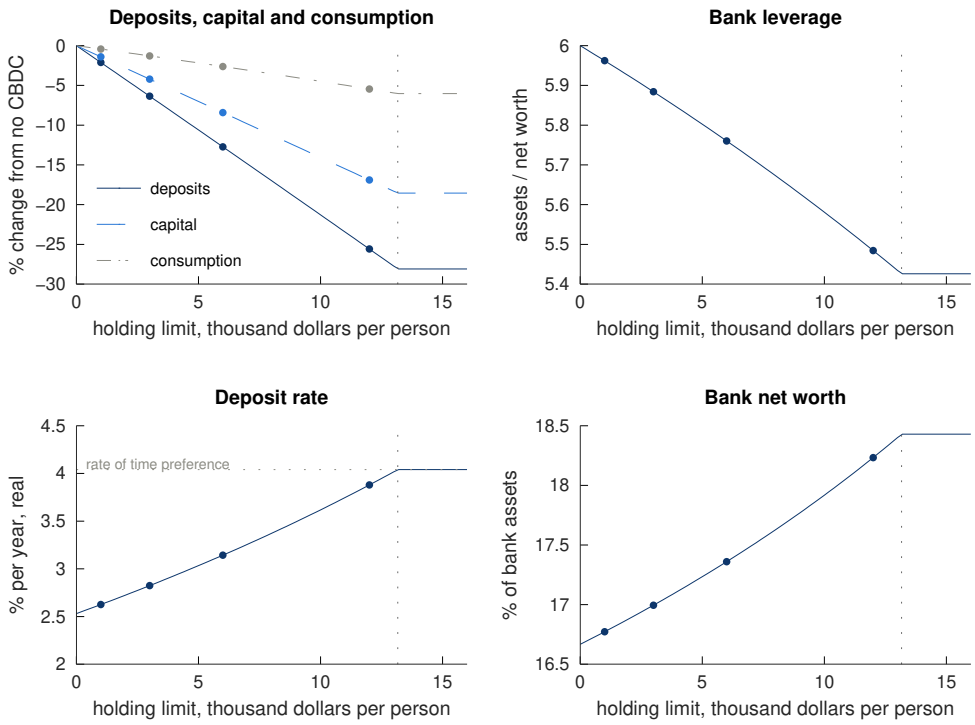


Figure 1: Steady states as a function of the holding limit. Each line connects 81 separately solved steady states, and the dots mark the four limits of Table 3. The dotted vertical line is at \$13,164 per person, the limit at which the meetings that accept deposits and CBDC are satiated.

5 Result 1: CBDC causes disintermediation

Table 4 shows that a holding limit of \$6,000 lowers deposits by 12.7 percent and the capital stock by 8.4 percent.

The mechanism in three steps. The first step is the liquidity premium on deposits. CBDC is part of the balances $A_{DE,t}$ in (32) that households can use in the meetings that accept deposits and CBDC. For a given amount of deposits, more CBDC makes households less constrained in these meetings, and therefore the liquidity premium LP_{DE} in (34) falls. By the condition for deposits (36), households then hold deposits only at a higher rate. With a limit of \$6,000 the premium on deposits falls from 150 to 89 basis points per year, and the deposit rate rises by 61 basis points.

The second step is the balance sheet of banks. A higher deposit rate lowers the return that a banker earns on net worth, from 4.40 to 4.32 percent per quarter. Net worth is

built from retained earnings, as in (20), so it is 8.3 percent lower in the new steady state. A lower return also lowers the value of continuing as a banker, so the incentive constraint (11) allows less leverage, 5.76 instead of 6.00. With less net worth and less leverage, banks hold 12.0 percent less capital.

The third step is the capital market. Households hold the capital that banks do not, and their share of the capital stock rises from 71.2 to 72.3 percent. The management cost (4) increases with that share, so by (5) households hold the larger share only if capital earns more. The return on capital rises from 5.04 to 5.60 percent per year, which requires a capital stock that is 8.4 percent smaller. Output is 3.3 percent lower as a result. The management cost is a cost in utility, so it uses up no output: output falls only because there is less capital.

Who bears the higher cost of deposits. Between the two steady states the deposit rate rises by 61 basis points and the return on capital by 56. The spread between the two, which is what a bank earns on each unit of assets, narrows only from 251 to 245 basis points. Banks therefore pass about nine tenths of the increase in their funding cost on to the return on capital. They can do so because households are the marginal holders of capital: the return on capital is determined by (5), and it rises as banks hold less. The cost of CBDC therefore falls mainly on the capital stock, and through it on output and consumption, and only to a small extent on the margin of banks.

Displacement of deposits. Each dollar of CBDC lowers deposits by \$1.21. The number is almost the same at every limit: 1.205, 1.207, 1.210 and 1.215 at \$1,000, \$3,000, \$6,000 and \$12,000. It has three parts. Deposits and CBDC are added together in the balances $A_{DE,t}$, so inside these meetings they are perfect substitutes, and a dollar of CBDC replaces 99.5 cents of deposits. A further 20.1 cents arise because the economy is smaller: consumption is lower, households need 2.1 percent fewer balances in total, and deposits make up the difference. The remaining 1.4 cents arise because each dollar of deposits pays more. When deposits and CBDC are both measured relative to output, the displacement is 0.89, again at every limit (0.894 to 0.888).

The constant rate of displacement follows from the assumption that deposits and CBDC are perfect substitutes in the meetings that accept both. It is in contrast to Bidder, Jackson and Rottner (2025), whose aggregator of deposits and CBDC has a constant elasticity of substitution, so that displacement declines as CBDC grows, and who find an interior optimum. Here nothing bends the relation until the meetings are satiated, at a limit of \$13,164, where displacement stops.

What the result does and does not show. Perfect substitutability is an assumption, so the constant rate of displacement is partly built in. The right reading is not that

displacement is constant as a matter of fact. It is that, in this model, the comparison of steady states does not single out a limit: a higher limit brings proportionally more of the same effects, up to the point of satiation. The comparison is also one between steady states, and it says nothing about the transition from one to the other.

6 Result 2: banks become safer

The adjustment that makes banks smaller also makes them safer. Leverage ϕ is assets divided by net worth, so each unit of assets is financed by $1/\phi$ of net worth and $1 - 1/\phi$ of deposits. Without CBDC banks hold 16.7 cents of net worth for each dollar of assets. With a limit of \$6,000 they hold 17.4 cents, and with \$12,000, 18.2. Net worth is what a bank can lose before its depositors are affected. In a steady state the solvency buffer (45) is $BUF = (R^b - R^d) + R^d/\phi$: the spread that the bank earns on its assets, plus what it does not owe because a share $1/\phi$ of the assets is financed by its own net worth. With a limit of \$6,000 the second term rises from 0.1677 to 0.1750, because leverage falls from 6.00 to 5.76. The first term falls slightly, from 0.0063 to 0.0061, because the spread narrows. The buffer rises from 0.1740 to 0.1811, by 4.1 percent, and the whole increase comes from lower leverage.

For a sense of scale, the buffer can be translated into the share of banks that would be insolvent if their returns differed, as explained in Section 2.7. That share, p, falls from 0.256 percent per quarter without CBDC to 0.179 at \$6,000, by 30 percent. The size of the fall depends on the normal distribution that is assumed: with a Laplace distribution and the same anchor it is 19 percent. The buffer and the net worth of banks do not depend on such an assumption.

The second measure moves in the same direction. The recovery ratio in a run rises from 1.118 without CBDC to 1.130 at \$6,000 and 1.143 at \$12,000. Most of the rise comes from the balance sheet: with lower leverage there are fewer deposits to repay out of each unit of assets. The liquidation price hardly changes, from 0.924 to 0.926 at \$6,000. Section 8 asks how large a shock has to be to bring the ratio below one.

The trade-off. The cost and the benefit of a holding limit are two sides of one adjustment: a banking system that is smaller and has more net worth for each unit of assets lends less and is further from insolvency. Table 5 puts the two sides next to each other. For each percent of deposits that is lost, the buffer widens by 0.29 percent at \$1,000 and by 0.36 percent at \$12,000. The terms of the trade therefore change only moderately with the limit. A higher limit means more of the same trade, and the comparison of steady states does not say how much of it is desirable.

Table 5: Costs and benefits of a holding limit, percent change from the economy without CBDC

	\$1,000	\$3,000	\$6,000	\$12,000
Deposits	−2.1	−6.4	−12.7	−25.6
Capital	−1.4	−4.2	−8.4	−16.9
Consumption	−0.4	−1.3	−2.6	−5.5
Bank leverage	−0.6	−1.9	−4.0	−8.6
Solvency buffer	0.6	1.9	4.1	9.2
Recovery ratio in a run	0.2	0.5	1.0	2.2
Rise in the buffer, per percent of deposits lost	0.29	0.30	0.32	0.36
Rise in recovery ratio, per percent of deposits lost	0.07	0.08	0.08	0.09

What the result does and does not show. Safer has a specific meaning here. No bank fails in the model, and p is a statistic. What the model delivers is that banks hold more net worth against their assets and that depositors would recover more in a run. Whether that is worth a smaller capital stock is a question about welfare, and this paper does not answer it. An answer would have to weigh lower consumption in the centralized market against higher consumption in the meetings of the decentralized market that accept CBDC, and against a risk of bank failure that households in the model do not price.

7 Result 3: CBDC is structural, not stabilizing

Each economy is hit by a fall in productivity and by a fall in capital quality, the two shocks in (25), each of one standard deviation. Only adverse shocks are reported. After a favorable capital quality shock, the balances that can be used in type DE meetings can exceed what those meetings need; the liquidity premium LP_{DE} then reaches zero, and the equations used to solve the model no longer hold. With a limit of \$12,000 this happens for a shock of 0.28 standard deviations. After adverse shocks the premium and the multiplier on the limit stay positive at every limit, also for shocks of two standard deviations.

The responses are almost the same at every limit. Figure 2 shows the responses to the capital quality shock, Figure 3 those to the productivity shock, and Table 6 gives the main numbers. After the capital quality shock, output falls by at most 0.52 percent without CBDC and by 0.54 percent with a limit of \$6,000. After the productivity shock the two numbers are 1.19 and 1.18. The two paths of output never differ by more than 0.05 percentage points. Consumption, investment and the price of capital show the same pattern.

The reason is that a binding limit leaves CBDC with no dynamics of its own. Households hold $e_t = \bar{e}$ in every period, so the amount of CBDC does not respond to a shock

and can neither absorb nor amplify it. A holding limit changes the steady state around which the economy fluctuates, and little else.

The differences that exist come from leverage. By (20), net worth falls on impact by about $\sigma_b \phi$ times the fall in the return on bank assets. That factor is 5.70 without CBDC, 5.47 at \$6,000 and 5.21 at \$12,000, so the same shock removes a smaller share of net worth when the limit is higher: 8.7 percent without CBDC, 8.5 at \$6,000 and 8.2 at \$12,000 after the capital quality shock. Table 6 shows that the effect on output is small.

Fragility along the path can be read from the solvency buffer. The deposit rate and the leverage in (45) are set before the shock, so on impact the buffer falls by exactly the fall in the return on bank assets: by 0.015 to 0.016 after the capital quality shock and by 0.008 after the productivity shock. The fall is almost the same at every limit, and the level from which it starts is not. With a limit of \$12,000, the buffer at its lowest point after the capital quality shock is 0.174, the value it has in the steady state without CBDC. The higher buffer of Section 6 is therefore kept through the shock.

The size of these responses depends on the adjustment cost of investment, because bank net worth moves with the price of capital: on impact after the productivity shock, 97 percent of the fall in the return on bank assets is the fall in the price of capital. The comparison across limits does not depend on it. With η_i at half or at twice its value, output falls by at most 1.31 or 1.07 percent after the productivity shock, in place of 1.19, and the paths of output with a limit of \$6,000 and without CBDC still differ by no more than 0.05 percentage points.

Relation to Paul, Ulate and Wu. Paul, Ulate and Wu (2025) find "the reactions of various macroeconomic indicators to standard monetary policy and technology shocks are remarkably similar" across CBDC regimes and that "transitory shocks have a limited impact on bank equity and lending capacity", while the regimes nonetheless "have significantly different welfare implications". Their design margin is the remuneration rate of CBDC and not a holding limit, so the result here is independent confirmation along a different dimension of the design.

Two qualifications apply. Both shocks are real. Money growth is constant and the rate on CBDC is fixed, so the model has no monetary policy shock, and the result says nothing about the transmission of monetary policy. And the responses come from a linear solution around each steady state, for shocks small enough that the holding limit keeps binding.

Table 6: Responses to adverse shocks of one standard deviation, in percent of the steady state of each economy. The solvency buffer is in levels

	No CBDC	\$1,000	\$3,000	\$6,000	\$12,000
Capital quality shock					
Output, largest fall	−0.52	−0.53	−0.53	−0.54	−0.57
Consumption, largest fall	−1.07	−1.07	−1.07	−1.06	−1.04
Price of capital, on impact	−0.54	−0.54	−0.55	−0.56	−0.58
Bank net worth, on impact	−8.71	−8.67	−8.59	−8.47	−8.18
Bank leverage, on impact	6.74	6.69	6.57	6.38	5.94
Capital held by banks, largest fall	−2.28	−2.30	−2.33	−2.38	−2.52
Solvency buffer, lowest level	0.1587	0.1598	0.1620	0.1656	0.1743
Productivity shock					
Output, largest fall	−1.19	−1.19	−1.19	−1.18	−1.18
Consumption, largest fall	−0.97	−0.97	−0.97	−0.97	−0.97
Price of capital, on impact	−0.75	−0.75	−0.76	−0.76	−0.77
Bank net worth, on impact	−4.38	−4.36	−4.32	−4.26	−4.12
Bank leverage, on impact	2.79	2.76	2.69	2.58	2.32
Capital held by banks, largest fall	−0.84	−0.85	−0.88	−0.92	−1.03
Solvency buffer, lowest level	0.1663	0.1674	0.1696	0.1733	0.1821

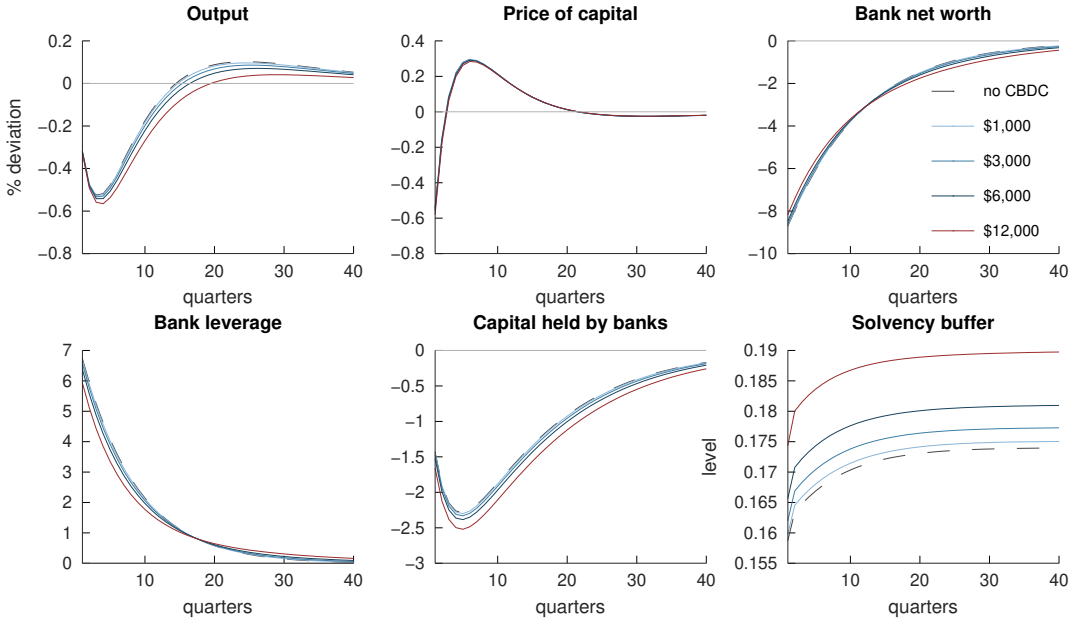


Figure 2: Responses to an adverse capital quality shock of one standard deviation. Percent deviations from the steady state of each economy; the solvency buffer is in levels.

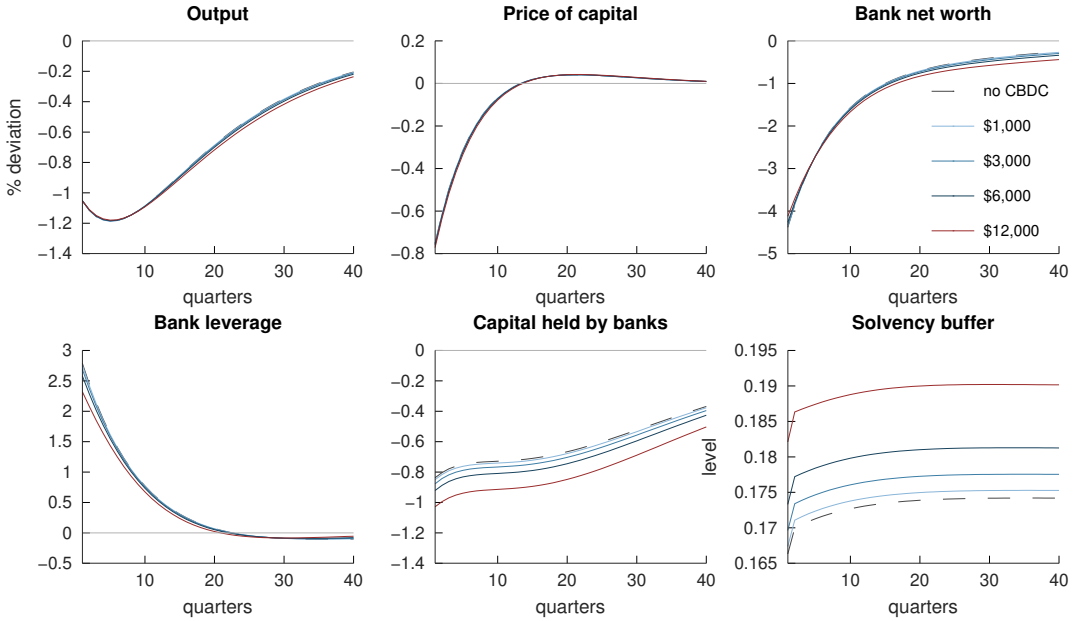


Figure 3: Responses to an adverse productivity shock of one standard deviation. Percent deviations from the steady state of each economy; the solvency buffer is in levels.

8 Result 4: runs are harder to trigger, up to a point

Without a shock there are no runs. The recovery ratio is above one in every steady state of Table 4, so the run probability (48) is zero. A run becomes possible only after a shock that brings the recovery ratio below one, and the size of that shock measures how far an economy is from a run.

The shock is a fall in the rental rate of capital, as in Gertler and Kiyotaki (2015). The rental rate falls by z in logs in the period of the shock and returns to its steady-state value at the rate at which productivity does. For each economy the model with runs of Section 2.8 is solved for a range of values of z, and the threshold is the value at which the recovery ratio in the period of the shock equals one. A higher threshold means that a run is harder to trigger.

Table 7: Runs and the holding limit. The threshold is the fall in the rental rate of capital, in logs times 100, at which the recovery ratio equals one. The last column is its change from the economy without CBDC, in percent

Limit	Liquidation price	Recovery ratio	Threshold	Change
No CBDC	0.924	1.118	45.5	–
\$1,000	0.925	1.120	45.6	0.2
\$3,000	0.925	1.124	45.8	0.6
\$6,000	0.926	1.130	46.1	1.3
\$12,000	0.927	1.143	46.7	2.7
\$13,164	0.928	1.146	46.9	3.0
\$16,000	0.904	1.118	34.7	−23.8
\$20,052	0.884	1.094	25.5	−43.9

Table 7 reports the results. Without CBDC a run requires a fall in the rental rate of 45.5 percent, about 46 times the standard deviation of the productivity shock of Section 7. This is a crisis and not a recession of the usual kind, and the threshold should be read as a distance and not as a forecast. With a holding limit the threshold is higher: 46.1 percent at \$6,000 and 46.7 at \$12,000. The reason is the one of Section 6: with lower leverage there are fewer deposits to repay out of each unit of assets. The effect is small: the threshold is 1.3 percent higher at \$6,000 and 2.7 percent higher at \$12,000 than without CBDC.

Limits above the point of satiation. The last three rows of Table 7 go beyond the limits considered so far. At \$13,164 the meetings that accept deposits and CBDC are satiated, and a higher limit no longer changes the steady state of banks. It still binds, up to \$20,052, because households want more CBDC for the type E meetings. Over this range the threshold falls, from 46.9 percent at \$13,164 to 34.7 at \$16,000 and 25.5 at \$20,052. Figure 4 shows the whole range.

The steady state is the same in these three rows. What differs is the stock of CBDC that households hold while banks recover from a run. After a run deposits start from zero, so their liquidity premium is high; funding is then cheap for the banks that restart, and they rebuild quickly. The CBDC that households keep holding lowers that premium. The larger the stock of CBDC, the slower banks rebuild, the longer households have to hold the capital, and the lower the liquidation price: 0.928 at \$13,164 and 0.884 at \$20,052. Below the point of satiation a higher limit lowers leverage and the liquidation price changes little. Above it, leverage no longer falls and the liquidation price does.

Three qualifications apply to this part of the result. In this range the liquidity premium LP_{DE} is zero in the steady state, so before a run deposits are no longer scarce as a means of payment. The range itself, from \$13,164 to \$20,052, depends on the share of type E

meetings, which is assumed. And the result rests on the treatment of liquidity during the recovery from a run, described below. With these qualifications, resilience to runs is highest at the limit at which deposits just stop carrying a liquidity premium. Below it a higher limit helps a little. Above it a higher limit leaves the steady state unchanged and makes a run easier to trigger.

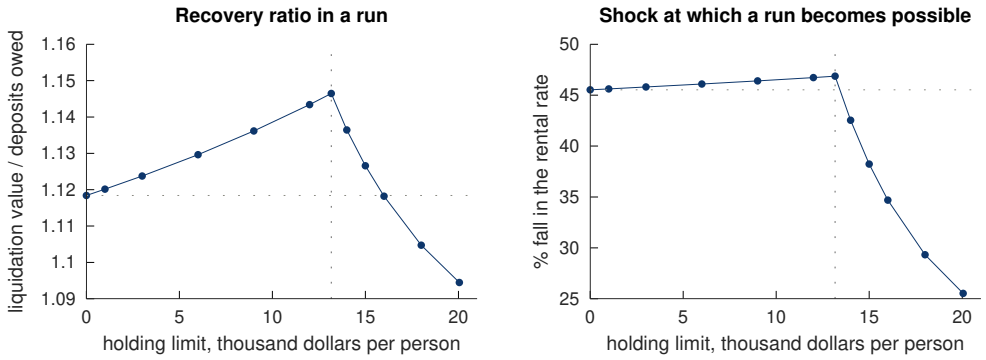


Figure 4: The recovery ratio and the threshold shock as functions of the holding limit. The dotted vertical line is at \$13,164 per person, the point of satiation, and the dotted horizontal line is the value without CBDC.

Relation to Bidder, Jackson and Rottner. In Bidder, Jackson and Rottner (2025) CBDC is also a safe asset to which depositors can run, which lowers the cost of running. That margin is absent here: a run is total by construction, and where depositors put the proceeds does not enter the recovery ratio (47). What this model contains is the other margin, how much depositors recover. The two papers compute two halves of the same question, and the net effect is one that neither settles alone.

What the result does and does not show. The calculation has four limits. Output and the capital stock are held fixed, so investment does not respond during the recovery. The shock enters only through the rental rate of capital, and it is far larger than the shocks of Section 7. In the period of the run itself neither deposits nor CBDC provide liquidity services; a fuller treatment would let households use the CBDC they hold in that period, which would matter for the comparison across limits. And a run remains a matter of coordination among depositors: the model determines when a run is possible, not whether one occurs.

9 Conclusion

In this model, CBDC is a nearly perfect substitute for deposits in the decentralized market, and a limit on holdings of CBDC determines how much of the payment role of deposits the central bank takes over. The liquidity premium that deposits earn there is what makes them a cheap source of funds for banks, and the limit decides how much of that premium remains.

With a limit of $6,000 per person, deposits are 12.7 percent lower than without CBDC, the capital stock 8.4 percent, output 3.3 percent and consumption 2.6 percent. Each dollar of CBDC lowers deposits by $1.21, at every limit. Banks become smaller and safer at the same time: leverage falls from 6.00 to 5.76, and banks hold 17.4 cents of net worth for each dollar of assets, up from 16.7. The fall in the rental rate of capital at which a run becomes possible is 1.3 percent larger. The paths of output after shocks to productivity and to capital quality differ by no more than 0.05 percentage points from those without CBDC.

The cost and the benefit of a limit are two sides of one adjustment. A banking system that is smaller and holds more net worth for each dollar of assets lends less and is further from insolvency. A higher limit means more of both, on terms that change only moderately with the limit. How the two should be weighed is a question about welfare that the paper leaves open. The limit changes the steady state and hardly the response to shocks: while it binds, the amount of CBDC does not respond to them.

The effect on runs is not monotone. Up to $13,164 per person, the limit at which deposits stop carrying a liquidity premium, a higher limit makes a run slightly harder to trigger. Above it a higher limit no longer changes the steady state of banks, and it makes a run easier to trigger. The CBDC that households hold lowers the liquidity premium on deposits while banks recover from a run, so banks rebuild more slowly and the price at which capital is liquidated in a run is lower. At $20,052, the amount that households would hold without a limit, a run becomes possible after a fall in the rental rate of 25.5 percent, against 45.5 percent without CBDC. In Bidder, Jackson and Rottner (2025) CBDC raises the risk of runs because depositors can run to it. That margin is not in this model. The result here is that a large stock of CBDC can make a run easier to trigger through the recovery of banks alone, without any flight to CBDC.

Four assumptions should be kept in mind when the numbers are read. The central bank does not lend the funds that households move into CBDC back to banks. Brunnermeier and Niepelt (2019) show that such lending can leave banks and the allocation unchanged; the model does not say how much of the fall in deposits and capital would remain if the central bank lent to banks. All deposits serve as a means of payment, so the whole of the deposit funding of banks competes with CBDC; deposits that are held only as savings would not. Deposits are real claims, so surprises in inflation do not change the net worth of banks. And CBDC does not replace cash: the meetings that accept only cash are the

same in every economy.

Two extensions follow from these assumptions. The first lets the central bank lend to banks. The second lets depositors who run hold CBDC and use it for payments in the period of the run. That would put the margin studied by Bidder, Jackson and Rottner (2025) and the margin studied here into one model.

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