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CBDC and banks: Disintermediating fast and slow*

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Abstract

We examine the impact of a retail central bank digital currency, combining survey evidence from German households with a macroeconomic model featuring endogenous systemic bank runs. The survey reveals non-trivial demand for retail CBDC as a substitute for bank deposits in normal times ("slow disintermediation") and increased withdrawal risks during financial distress ("fast disintermediation"). Informed by the survey, the model indicates that introducing a retail CBDC might reduce financial stability because CBDC offers *storage-at-scale* - making it attractive to run to. We estimate an optimal holding limit which chokes off fast disintermediation and *enhances* financial stability by shrinking a fragile banking system.

Keywords: Central Bank Digital Currencies, Financial Crises, Disintermediation, Bank Runs, Banking System, Money
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> The novelty with CBDCs is that they would provide access to a safe asset that – unlike cash – could potentially be held in large volumes, in the absence of safeguards, and at no cost, accelerating 'digital runs'. Such runs could even be self-fulfilling. . .

Fabio Panetta, 2022, *IESE Business School Banking Initiative Conference on Technology and Finance*

> A widely available CBDC would serve as a close — or, in the case of an interest-bearing CBDC, near-perfect — substitute for commercial bank money. This substitution effect could reduce the aggregate amount of deposits in the banking system, which could in turn increase bank funding expenses, and reduce credit availability or raise credit costs for households and businesses.

Board of Governors, 2022, *Money and Payments: The U.S. Dollar in the Age of Digital Transformation*

1. Introduction

Advances in payment technologies have led central banks to consider issuing central bank money in digital form to the public, commonly referred to as retail Central Bank Digital Currency (CBDC).[1] The potential impact of CBDC on the banking system has been hotly debated with two phenomena receiving particular attention: *'slow disintermediation'*, by which CBDC competes with bank deposits in normal times, leading to more expensive funding and a shrinking of the sector, and *'fast disintermediation'*, by which CBDC provides an especially convenient asset to convert to and hold in times of banking stress, enhancing the scope for bank runs.

Fast and slow disintermediation may interact and, thus, should be analysed jointly. This paper provides such an analysis through two classes of contribution - empirical and theoretical. We document novel evidence from a survey of German households regarding their projected use of a hypothetical digital Euro. We then build a structural macroeconomic model featuring CBDC and endogenous *systemic* bank runs and explore the implications of CBDC for welfare, the banking sector and policy design. The model is matched to key European aggregate moments and is also partly informed by our survey data in the absence of real world information on CBDC adoption. In allowing for both fast and slow disintermediation we show that some of the concerns mentioned in the quotes above may be allayed. Suitably-designed CBDC - in particular, with holding limits - may induce a desirable welfare effect precisely because it *does* disintermediate banks, reducing the fragility of a system prone to runs.

Clearly, in the absence of a functioning CBDC it is difficult to establish targets for economic modeling. As such, surveys about hypothetical usage, particularly in such an influential country as Germany, are especially useful. Based on the Deutsche Bundesbank's Survey on Consumer Expectations we observe how people might allocate funds across different asset classes in various contingencies, where the assets considered include

[1] The focus of this paper is entirely on retail CBDC, which is also commonly referred to as digital cash.

cash, bank deposits, and digital Euro deposits. Specifically, we ask how they would allocate funds in 'normal times', first in the absence of a CBDC, then in the presence of a CBDC (both with and without remuneration). We also ask how they might *reallocate* funds initially held in a commercial bank account in times of 'banking stress'.

A key finding from the survey is that Germans appear open to CBDC. Even when offered an unremunerated digital Euro, in 'normal' times, just under half of respondents project positive holdings – a group we refer to as being 'keen' to use the digital Euro. Among these, the average allocations of funds to CBDC and cash are similar - a striking finding in a country with an anecdotally strong attachment to cash. Hypothetical adoption is, unsurprisingly, even higher in the case of a CBDC remunerated at or above the rate paid on their bank deposits or in times of banking stress.

When we confront respondents with a hypothetical period of *general* banking distress, more than half of respondents project withdrawing a positive amount to digital Euro. This tendency is stronger among those whom we randomly treated with additional information about the relative safety of central-bank backed money, in comparison with money issued by commercial banks. Notably, the availability of the CBDC is associated with an overall increase in withdrawals from bank accounts, rather than simply inducing substitution away from cash as the asset to run to.

These empirical results have important implications for banks, from the perspective of both slow and fast disintermediation. Our theoretical contribution is to build a medium scale DSGE framework - solved globally - that is capable of addressing these issues, and which can be used to analyse a variety of emerging policy questions around CBDC.

Our model builds upon the now familiar foundations of the New Keynesian framework, augmented with a banking sector in which banks face risk-shifting incentives. These incentives lead to endogenous leverage constraints in equilibrium that vary with the level of aggregate risk in the economy. The banking sector occasionally faces system-wide runs with probabilities that are dependent on the endogenous state of the economy and, in particular, on bank leverage (see Adrian and Shin (2010), Nuño and Thomas (2017), Gertler et al. (2020) and Rottner (2023)).

CBDC competes with bank deposits in normal times, reducing the liquidity premium obtainable by banks on their deposits. This slow disintermediation shrinks the banking system and, all else equal, would imply reduced run-risk. The argument has flavors of the theory of the second best - an already fragile system is reduced in scale. However, the introduction of CBDC in its simplest form may aggravate the possibility of runs implying a net negative effect of CBDC on financial stability.[2]

[2]Unlike cash, CBDC offers *storage-at-scale* and unlike deposit insurance, it offers *instant access* even in a *systemic* banking crisis. It is well known that deposit insurance schemes are not funded for such systemic events, but for idiosyncratic. Our focus is not on idiosyncratic runs from one bank to another, where it is *a priori* unclear that the presence of CBDC should have any influence. For frontier work

At sufficiently high leverage, multiple equilibria emerge in which beliefs of a run can be self-confirming, as in Diamond and Dybvig (1983). During a run, households stop rolling over their deposits and incumbent banks cannot fund their assets, leading to a drop in the value of their holdings, inducing losses that justify the run in the first place. The drop in value reflects in part the assumption that households (and the central bank) are 'non-expert' investors: to absorb assets no longer fundable by incumbent banks, they require a substantial price discount (Kiyotaki and Moore (1997) and Shleifer and Vishny (1992)). Newly formed banks - replacing failed incumbents - are alternative investors to households, to some extent. But they are also subject to capital constraints and, at their initially low levels of net worth, can only play a limited role in 'catching the falling knife' of abandoned investments. Indeed, this role may be further constrained in the presence of a CBDC owing to what we call its 'storage at scale' characteristic.

CBDC is a completely safe alternative asset with payment capabilities *and* the scope to be held in arbitrarily large quantities. The former is a property of cash, while the latter is not. We capture this by making the (realistic) assumption that the costs of holding cash increase rapidly with the amount held, in contrast to CBDC holdings, which do not exhibit such costs. In a run, the already shrunken banking system faces particular funding pressure if a CBDC is available. The fact that CBDC is an ideal 'haven' asset in a run makes it even more difficult for the newly formed banks to fund themselves and carry out an intermediation role, which in turn exacerbates asset price declines. The increased severity of the run means that the economy is more vulnerable and, on net, we observe the introduction of CBDC increasing the probability of runs.

We then ask if one can design a framework to retain the financial stability benefits of slow disintermediation reducing the size of the banking system, while avoiding increased risk of fast disintermediation. Specifically, we consider introducing a holding limit on CBDC, which many countries are now discussing. We show that – with carefully calibrated limits – the introduction of CBDC can *enhance* financial stability. In normal times, holding limits should allow households to almost fully satiate their demand for CBDC while preventing the holdings from being arbitrarily large and exacerbating runs. Based on our preferred calibration, our model suggests an optimal limit level ranging between €1500 and €2500 for CBDC holdings. While our model makes a substantial contribution to realism in modeling CBDC, the framework still omits several real-world dimensions so these numbers should be treated with care. Nevertheless, our findings are in the realm of values discussed in relation to the digital Euro.

While our focus is on unremunerated CBDC – reflecting the emphasis of current policy debates – we also consider whether remunerated CBDC might mitigate run risks. We assume the remuneration rate is set at a fixed spread below the standard policy rate,

theoretical work on heterogenous banks see Bellifemine et al. (2022).

which is assumed to follow a Taylor rule. Even in the absence of holding limits, CBDC can then enhance financial stability, as it endogenously becomes much less attractive in runs. This reflects the fact that the policy rate - and thus the CBDC remuneration rate - declines dramatically as the economy weakens. This has the effect of disincentivizing CBDC holdings.

Literature Review. The literature on central bank digital currencies has grown rapidly in recent years. Several surveys now exist, such as those focusing on retail CBDC by Ahnert et al. (2022), Infante et al. (2022), Chapman et al. (2023), wholesale CBDC pilots, such as Bidder (2023), and those that span both, such as BoE (2020), BIS (2021) and BIS (2023).

The implications of CBDC for the banking system and for financial stability more generally have been a focus of recent study. Andolfatto (2020), Whited et al. (2022), Keister and Sanches (2022), Jackson and Pennacchi (2021) and Chiu et al. (2022) focus on what we would term 'slow disintermediation'. They discuss how bank funding costs and, ultimately, lending might be influenced in steady state. See also Chiu and Monnet (2023) for a framework featuring *other* types of money (stablecoins and tokenized deposits).

Both slow and fast disintermediation are discussed in Brunnermeier and Niepelt (2019), Adalid et al. (2022) and Angeloni (2023), while a host of papers have recently begun to examine financial fragility in particular (BoE (2020) and Bindseil (2020) for early discussions). Befitting the importance of the subject, there are many recent contributions, including Fernández-Villaverde et al. (2021), Kumhof and Noone (2021), Williamson (2022), Keister and Monnet (2022), Kim and Kwon (2022), Ahnert et al. (2023), Niepelt (2023), Muñoz and Soons (2023) and Paul et al. (2024). Perhaps closest to our work (in the intuition of offsetting steady state and run phenomena) are Kim and Kwon (2022), Keister and Monnet (2022) and Ahnert et al. (2023). However, our contribution is the first to deal with these issues in the context of a medium scale New Keynesian model, opening the door to the sort of realistic policy analysis for which such models are commonly used.

Embedding CBDC in generic macroeconomic models has been achieved in Burlon et al. (2024), Barrdear and Kumhof (2022), Abad et al. (2025) and Assenmacher et al. (2023) for closed economies, and work has begun on incorporating it into open economy frameworks (see Pinchetti et al. (2023), for example). Our work is distinct from these in that not only do we offer a medium scale DSGE model with a banking sector, but we do so in a non-linear model, globally solved.

In analyzing the role of CBDC holding limits we contribute to a hotly debated topic (see Panetta (2023b), ECB (2023), Angeloni (2023) and House of Commons (2023)). Nevertheless, there is little academic research, as yet, on this topic. Meller and Soons (2023) provide a thorough accounting-based analysis of bank balance sheet evolution, but do not offer a macroeconomic model.

We are not the first to obtain survey evidence relevant to CBDC. Some surveys not initially *designed* to be about CBDC can be informative - such as that analyzed by Li (2023) to elicit predictions for CBDC preference based on existing motivations for cash and bank deposit usage. Other surveys *have*, however, been specifically designed to ask about CBDC. Like ours, these surveys typically find substantial heterogeneity among respondents and an important role for 'trust' in determining openness to CBDC in European countries (Bijlsma et al. (2021) in the Netherlands, Abramova et al. (2022) in Austria), in Korea (Choi et al. (2023)) and globally (Patel and Ortlieb (2020)). Bijlsma et al. (2021) also derive information on the response of households to remuneration rates. Our survey contributes to the literature in being from another substantial European country, Germany, where one might suspect different behavior - given the unusual attachment Germans appear to have to cash. We also tie our survey to a structural macroeconomic model to discipline our structural analysis. Importantly, we include questions related to runs, which is a rare inclusion in any survey, let alone one about CBDC. In contemporaneous work, Sandri et al. (2023) find interesting evidence of the effect of treating households with news about Silicon Valley Bank (SVB) on households' perception of bank stability. We also exploit a randomly assigned treatment - a powerful approach - to explore the effect of emphasizing to households the relative safety and utility of CBDC.

Beyond CBDC-specific work, we of course build upon a rich literature analyzing financial frictions and crises within macroeconomic models with financial intermediaries. As in Rottner (2023) (drawing also on Nuño and Thomas (2017) and Gertler et al. (2020)) we assert fundamental information frictions that lead to endogenous state dependent leverage constraints. The constraints tighten (loosen) as risk increases (decreases) in the economy, generating a 'volatility paradox' (see Brunnermeier and Sannikov (2014)) where financial fragility builds during *apparently calm* periods. We also capture the intuition of risk management practices discussed in Adrian and Shin (2010). As such, we use state of the art components in our model to allow for runs, but in the context of the CBDC debate.

2. Survey Evidence

Since 2019, the Bundesbank has commissioned a Survey on Consumer Expectations. We included 5 questions related to CBDC in the April 2023 wave, issued to approximately 5,700 respondents.

2.1. CBDC questions

The rubric at the start of our set of questions was as follows, where the section in *italic* font was only (randomly) presented to a half of the respondents:

> We will now turn our attention to the digital euro. The introduction of the digital euro is currently being investigated by the European Central Bank (ECB) and the national central banks of the euro area, such as the Bundesbank.
>
> The digital euro would be digital money that would be used like money on a current account. However, it would be issued and guaranteed by the ECB and the national central banks.
>
> *The digital euro would be exchangeable for euro in the form of cash at any time and also be used for payments at all times. By contrast, the availability of money on a current account with a private commercial bank depends to some extent on the stability of that commercial bank.*
>
> The digital euro would not replace cash or accounts with commercial banks, but would be an additional offering alongside these. The digital euro would enable everyday payments to be made digitally, quickly, easily, securely and free of charge throughout the euro area.

Given that we later ask about a remunerated version of CBDC so at this early point, we did not want strictly to align d€ with (zero-yielding) cash in the minds of the respondents. Note also, we explicitly refer to issuance and backing by central banks, and then emphasize some of the implications of this - and contrasts with commercial bank money - in the randomly assigned additional paragraph.

2.1.1. CBDC adoption in normal times

Our first batch of questions relate to CBDC adoption in 'normal times'. They consider a situation where d€ is absent (the *status quo*), a situation with a hypothetical unremunerated CBDC, and a situation with a remunerated CBDC. Specifically, the first question is:

> Now imagine you had €1,000 available each month to allocate across different asset classes. In this context, please assume that the digital euro does not yet exist.
>
> How much of the €1,000 per month would you hold as cash, deposit into your current account, or invest in other financial instruments

while the second question (after reminding the respondent of her previous answer) introduces the hypothetical unremunerated d€:

> Please now assume that the digital euro were to be introduced. Please also assume that you have a digital euro account that you can use to hold digital euro. You would receive no interest on this digital euro account.

The third question related to *remunerated* CBDC. We randomly split respondents into four groups. Each was offered a hypothetical d€ paying an interest rate of 100 basis points less, 50 basis points less, equal to, or 50 basis points more than the rate on their current (bank) account. Before answering, the respondents were reminded of their answer in the unremunerated case.

> Please now assume that you would receive an interest on your digital euro account that would be - *TREATMENT* - the interest rate on your regular current account at your bank.

Reflecting the idea that these questions related to 'steady state' behavior, we asked the respondents how they would allocate a regular hypothetical amount per month among different asset classes.

2.1.2. CBDC in a stressed banking environment

Respondents were then presented with a hypothetical situation of general strains in the banking sector. We began by inviting the respondent to consider how she might *reallocate* a stock of *existing* bank deposits (€5,000, in contrast to the €1,000 flow):

> The next section is about money that you already have on your regular current account at your bank. Imagine that you had €5,000 on your current account.
>
> In addition, please assume that sector according to credible news sources there are doubts about the stability of the banking. This could lead to a banking crisis that could also affect your bank. If this were to happen, you might have problems accessing your current account at short notice to withdraw money or make credit transfers.
>
> In this situation, how much of the €5,000 would you withdraw as cash from your regular current account or invest in other financial instruments?

Then, after reminding the respondent of her previous answer we ask the analogous question, but in the presence of a hypothetical d€:

> Now please imagine that a digital euro was available as an alternative to cash and other financial assets. Please also imagine that you would receive no interest on the digital euro.
>
> *Please remember that the digital euro would be able to be exchanged for euro in the form of cash at any time and also be used for payments at all times.*

where, again, the *italic* segment was only displayed to the group who (as aforementioned) were randomly chosen to receive extra information about the relative safety of a central bank-backed money.

2.2. Survey results

In this section, we outline the results of the survey, distinguishing between normal times and periods of banking stress.

2.2.1. CBDC adoption in 'normal times'

A little under half of the respondents project a desire for d€ in the unremunerated case (43.2%). However, if d€ offers the same remuneration as the respondents' current accounts, then that number rises to 54.3%. The adoption rate declines (rises) by about 23 (14) percentage points in moving from remuneration at the current account rate, to remuneration at 50 basis points lower (higher).

In the left panel of figure 1 we see the average portfolio allocation across the survey sample, including *all* respondents. Looking at the portfolios, the projected average share of CBDC is around 10%. The average d€ to cash ratio is around 66%, indicating substantial interest.[3] We observe movements out of all other asset classes when d€ becomes (hypothetically) available with the decline in bank deposits being proportionally the largest.

These results reflect the averaging of results from the large fraction of respondents who projected zero holdings of unremunerated d€ and those from 'keen' respondents who projected positive holdings. In the right panel of figure 1, we show results for 'keen' respondents. *If* these people are more reflective of how the broader population will behave, once the d€ is advertised and explained more widely - and once trust in the d€ is established - then it may contain predictive information about adoption in the medium term.

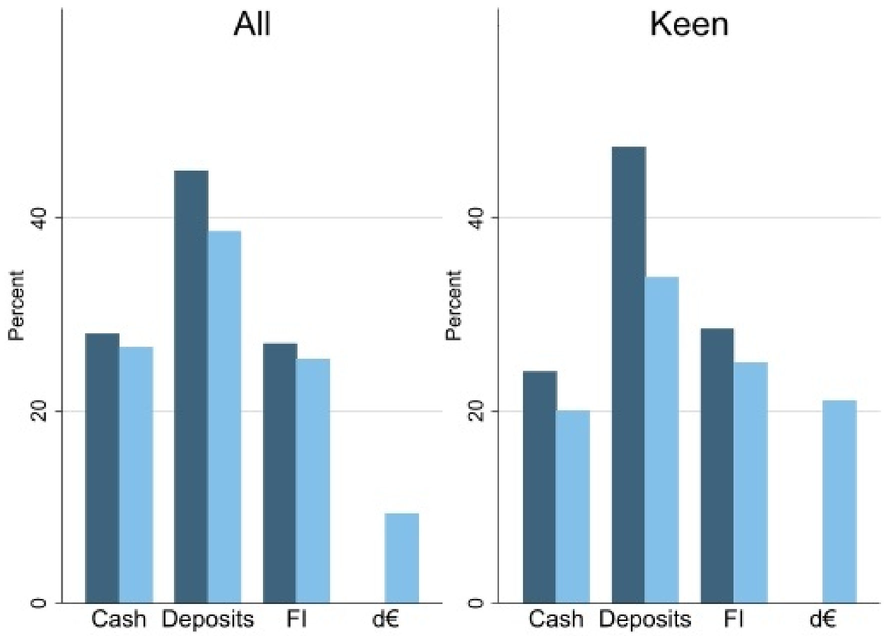

Figure 1: Portfolio decisions of households in normal times. Dark blue (left bar) displays shares without d€, while light blue (right bar) displays shares with d€. The columns correspond to cash, deposits, other financial instruments, d€ (from left to right). The left panel shows the average for the entire set of respondents. The right panel shows those with 'keen' ones (respondents with positive values projected for d€). Each chart refers to the unweighted survey sample.

Among the 'keen' group, unremunerated d€ is projected to be approximately 21% of the portfolio on average. Notably - given anecdotes of Germans' enduring affinity for physical money - this is slightly higher than the cash share. On (hypothetically) introducing d€ we see movements out of other asset classes. Table 1 shows these changes for various sub-samples of respondents. Cash and deposits decline, on average, by around 14% and 27% respectively.[4]

[3] This number diverges somewhat from what the figure might suggest, owing to Jensen's inequality.

[4] In terms of 'levels' (recalling that we are discussing shares to begin with) we see declines of around 4 percentage points and 14 percentage points. Note that the samples for calculation of percentage changes may be slightly different from those of the percentage point changes owing to the possibility of zero

	d€				Cash				Deposits			
	Q2		Q5		Q1 vs Q2		Q4 vs Q5		Q1 vs Q2		Q4 vs Q5	
	Mean	Median	Mean	Median	Diff.	% Diff	Diff	% Diff	Diff	% Diff	Diff	% Diff
All	9.37	0	19.27	10	-1.25	-4.16	-10.41	-13.94	-6.36	-13.36	-4.86	-23.35
Keen	21.10	20	28.43	20	-4.02	-13.52	-14.34	-19.60	-13.56	-26.75	-7.35	-28.35
Open	13.39	10	28.65	20	-2.32	-8.30	-14.91	-21.75	-8.88	-17.14	-7.24	-32.00
High Trust	12.28	5	25.18	20	-1.81	-7.76	-12.47	-19.7	-8.43	-16.97	-7.01	-27.68
Low Trust	4.58	0	10.4	0	0	3.26	-6.62	-8.37	-3.62	-7.85	-2.04	-22.78

Table 1: Projected unremunerated d€ holdings and withdrawal shares (based on Q2 and Q5) as well as changes in cash and deposit holdings after introduction of CBDC in Q2 and Q5, respectively. The different rows distinguish between all, keen, open, high trust and low trust respondent. The changes for deposits and cash are shown in percentage points and percent.

These shifts indicate that a significant fraction of respondents see d€ as an attractive substitute for assets that provide both payment and store-of-wealth services. Overall, there is a substantial shift out of extant forms of money - both physical and digital. In particular, the results indicate some 'slow' disintermediation resulting from the introduction of the d€.

We find that an influential determinant of desire for d€ is 'trust'. The survey asks respondents to rate their trust in the ECB, *ostensibly* in relation to its ability to deliver price stability. It appears that this variable may capture a broader concept of trust, however, as it correlates with answers to another question in the survey - whether the ECB has an advantage in providing digital payments via a d€, relative to private sector provision. Furthermore, respondents appear notably less likely to have high trust in the ECB if they were adults and based in East Germany when the Berlin Wall fell.

We observe the key importance of 'trust' for the adoption of the d€. Figure 2 shows the portfolio comparisons for the two groups. Note that we include respondents within both these groups who project zero holdings of dEUR so we are blending intensive and extensive margin patterns.

In probit analysis of the *extensive* margin (reported in the online appendix), being of high trust raises the probability of adoption by about 10 percentage points, while being *low* trust is associated with a dramatic 22 percentage point decline in the probability of adoption. Both these effects are highly statistically significant. Whether or not the respondent was an adult in pre-1989 East Germany is also statistically significant, even controlling for trust in the ECB. Experience of an authoritarian regime is associated with a reduction of approximately 6 percentage points, which chimes privacy concerns raised by those sceptical about a CBDC.

holdings, making the calculation of a percentage change ill defined.

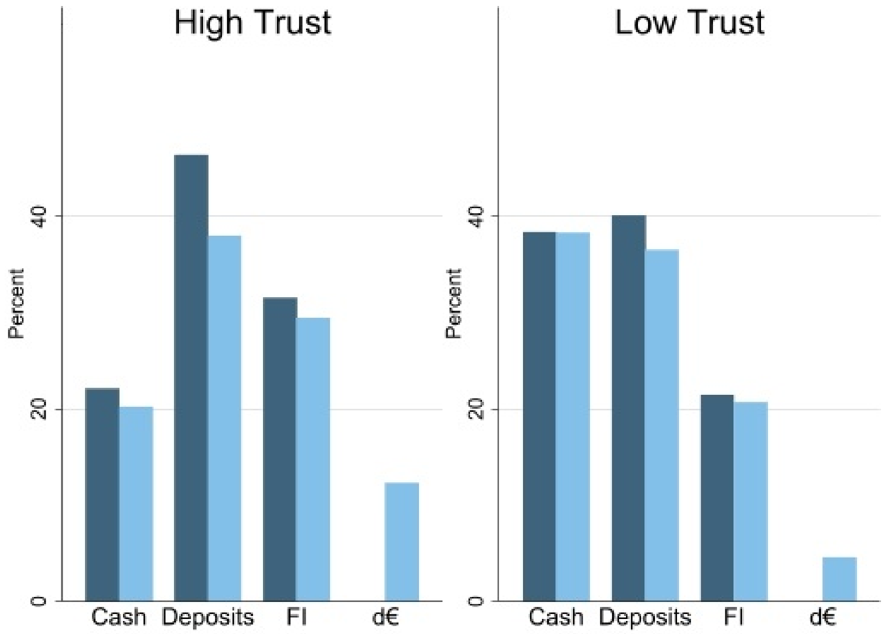

Figure 2: Portfolio decisions of high trust (left) and low trust (right) households. Dark blue (left bar) displays shares without d€, while light blue (right bar) displays shares with d€. The columns correspond to cash, deposits, other financial instruments, d€ (from left to right). Each chart refers to the unweighted survey sample.

2.2.2. CBDC and withdrawals in times of banking stress

We now consider the extent to which, and into what asset classes, households might withdraw funds from commercial bank accounts in times of bank stress. Figure 3 illustrates average withdrawal patterns for all respondents, and for the 'keen' group.

Given the complexity of the question it is instructive to see the impact of our treatment - giving half the respondents more information about the availability and convertibility of d€, relative to bank money. 58 percent stated they would withdraw to d€ among those who were treated with extra information, in contrast to 49 percent among those who did not receive the extra information. Interestingly, among those who projected zero d€ in normal times, approximately a third stated they would withdraw to it in times of banking stress. 35 (25) percent stated they would withdraw to d€ among those who were treated (not treated) with extra information.

Considering all respondents, we see that the dominant asset to withdraw to is cash, regardless of which sample we consider and regardless of the presence of d€. Looking across the whole sample, more than 50 percent of the bank deposits on average are projected to be withdrawn to cash, with this falling to a little over 40 percent in the presence of d€. Just over a fifth of deposits (on average) are left in bank accounts in the absence of d€ but this falls by around 5 percentage points - or around 23 percent - in the presence of d€, as shown in table 1. As such, introducing d€ does not only induce substitution from cash as an asset to 'run' to, but also exacerbates bank deposit withdrawals overall.

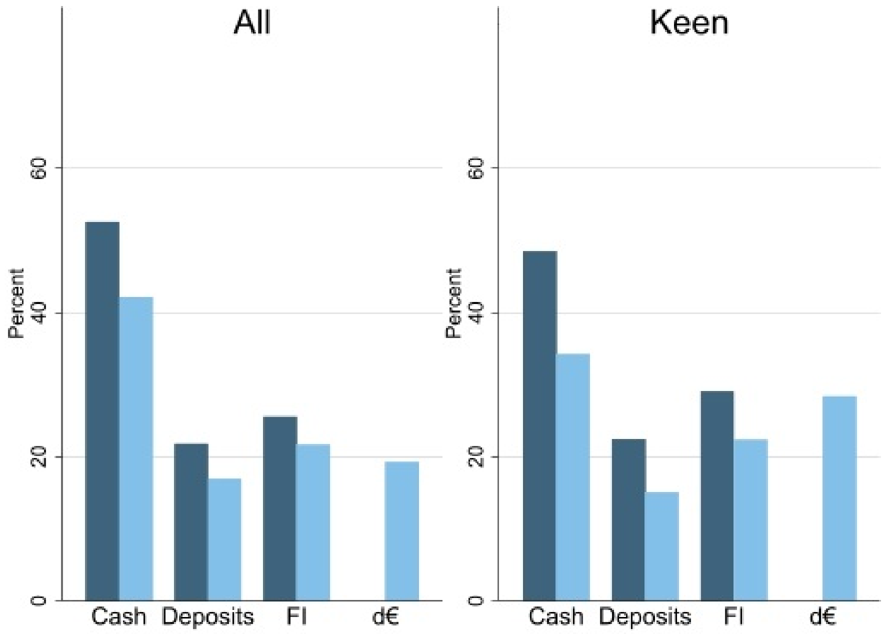

Figure 3: Average withdrawal shares of households during banking stress. Dark blue (left bar) displays shares without d€, while light blue (right bar) displays with d€. The columns are cash, deposits left in the account, other financial instruments, d€ (from left to right). The left panel shows the average for the entire set of respondents. The right panel shows those with 'keen' ones (respondents with positive values). Each chart unweighted.

Thus, there does appear to be a sense in which d€ is perceived as a desirable haven in times of banking stress and it apparently does increase the outflow from bank deposits by a non-trivial amount - an important factor incorporated in our model discussed below.

3. Model

Our model features two key components. First, it allows for financial fragility by incorporating a banking sector vulnerable to endogenous bank runs (see Rottner (2023) and Gertler et al. (2020)). Second, we allow for the coexistence of CBDC with other forms of money. We compare the economy in the absence and presence of CBDC, and under various design decisions on the implementation of CBDC.

3.1. Household

A representative household comprises workers and bankers with perfect within-household insurance. Banks die with probability $1-\theta$, at which point bankers return their net worth to the household. Simultaneously, new bankers enter each period and receive a transfer from the household. The household owns the non-financial firms in the economy, from which it receives profits. Additionally, the household pays taxes and receives payments (both lump sum) from the (Ricardian) government. The household can invest in: securities issued by non-financial firms, bank deposits that promise to pay a predetermined gross interest rate $\bar{R}_t$, physical cash and, if the central bank offers it, CBDC.[5]

3.1.1. Portfolio decision

Bank deposits *'promise'* in t a nominal face return of $\bar{R}_t$ in $t+1$, but the household receives only a fraction x_{t+1} of the promised return in the case of a run. The 'recovery ratio' x_{t+1} is endogenous. Thus the realized return on deposits is given by $x_t \bar{R}_{t-1}$ if there is a run in t.

While we abstract from deposit insurance, our main takeaways are robust provided some households believe an instantly convertible CBDC has advantages over an insured deposit in a *systemic* bank run. Deposit insurance schemes are typically funded for *idiosyncratic* runs – and emergency recapitalization schemes seen in the Great Financial Crisis are not codified. Thus, the insurer's ability to fully and quickly restore funds in a systemic crisis may well be doubted by some households, who choose instead to convert to CBDC, sparking a fast disintermediation (see also Ikeda and Matsumoto (2021) for a model with imperfect deposit insurance). Furthermore, in March 2023, around the time of the failure of Silicon Valley Bank, authorities felt the need to invoke a 'systemic risk exemption' and guarantee uninsured depositors (see Labonte (2024) for a discussion). Indeed, even after the systemic risk exemption was invoked there were further runs on many banks, as documented in Cipriani et al. (2024).[6] This suggests that in some contexts, even in a system with a robust deposit insurance framework (up to $250,000), runs with systemic implications are still relevant, and influence policy actions. Thus, aside from the fact that developing a heterogeneous banks model with CBDC and runs is beyond the scope of this work, it is independently important to consider systemic risks.

As in Gertler et al. (2020), we distinguish between beginning-of-period capital K_t used to produce output, and capital 'in progress' which will be transformed into productive capital at time $t+1$ after depreciation δ and an adjustment cost governed by the function Γ_I. It is convenient to refer to claims on capital-in-progress as securities, S_t, the amount of which evolves according to:

$$S_t = (1-\delta)S_{t-1} + \Gamma_I\left(I_t/S_{t-1}\right)S_{t-1}. \tag{1}$$

The households' end of period securities holdings, $S_{H,t}$, give them a direct ownership in the non-financial firms. Ownership entitles them to a stochastic rental rate Z_t and the security price is denoted Q_t.

[5] Implicitly, we also consider government bonds - nominally riskless assets that, to households, are not money-like. However, as discussed later, these will be in zero net supply and we abstract from them here.

[6] While we cannot speak directly to the current debate over the concentration of corporate treasury deposits in commercial banks, the importance of large corporate deposits (above deposit insurance thresholds) for run risk is only now being analyzed (see Rose (2023) and Sole (2024)).

Funding from households and banks are perfect substitutes from the perspective of firms. Total end-of-period securities holdings S_t are the sum of $S_{H,t}$, $S_{B,t}$ and $S_{CB,t}$ - securities held by households, commercial banks and the central bank, respectively.

Households may also hold balances in cash, Ca_t, incurring storage costs, $\psi(Ca_t)$. We assume that $\psi(Ca_t) > 0, \psi'(Ca_t) > 0$ and $\psi''(Ca_t) > 0$ if $Ca_t > 0$. This feature makes it expensive to hold very large amounts of cash, as is realistic. Following the functional form of Burlon et al. (2024), the costs are given by (with $\psi_m > 0$):

$$\psi(Ca_t) = \frac{\psi_m}{2} Ca_t^2 \tag{2}$$

The households may also hold CBDC, $D_{CB,t}$, if the central bank issues it. CBDC either pays a (nominally) riskless interest rate $R_{CB,t}$ from t to $t+1$ or are unremunerated, that is $R_{CB,t} = 1$, depending on the setup chosen by the central bank, discussed below.

3.1.2. Budget constraint

Given the above, the budget constraint of the household is

$$\begin{aligned}(1+s_t)C_t + Q_t S_{H,t} + Ca_t + D_t + D_{CB,t} + \psi(Ca_t) + T_t \\ = W_t L_t + (Z_t + (1-\delta)Q_t)S_{H,t-1} + \Xi_t + \Pi_t^{-1}\left(Ca_{t-1} + D_{t-1}R_t + D_{CB,t-1}R_{CB,t-1}\right)\end{aligned} \tag{3}$$

where Π_t is the inflation rate, T_t is lump sum transfers from households to the government and Ξ_t captures the remaining residual transfers between households, banks, non-financial firms and the government. Household consumption is denoted by C_t and their labor, L_t, is remunerated at W_t. s_t is transaction costs incurred in purchasing units of consumption, as in Schmitt-Grohé and Uribe (2010). The transaction costs depend on velocity, $v_t \equiv C_t/M_t$ where[7]

$$s_t = s_1\left(v_t + s_2 v_t^{-1} - 2\sqrt{s_2}\right) \tag{4}$$

Households can reduce the transaction cost by holding liquid assets, M_t:

$$M_t = \left[Ca_t^{\frac{\eta_m - 1}{\eta_m}} + \mu_d D_t^{\frac{\eta_m - 1}{\eta_m}} + \mu_{cb} D_{CB,t}^{\frac{\eta_m - 1}{\eta_m}}\right]^{\frac{\eta_m}{\eta_m - 1}} \tag{5}$$

3.1.3. Utility and optimality

The *lifetime* utility function of the household maximizes is

$$U_t = E_t\left[\sum_{\tau=t}^{\infty} \beta^{\tau-t}\left\{\frac{C^{1-\sigma^h}}{1-\sigma^h} - \chi\frac{L^{1+\varphi}}{1+\varphi} - \Gamma(S_{H,\tau}, S_{CB,\tau}, S_\tau)\right\}\right] \tag{6}$$

[7] The transaction cost function is chosen to satisfy a) $s(v) \geq 0$ b) $\exists \underline{v}$ such that $s(\underline{v}) = 0$ (satiation) c) $(v - \underline{v})s'(v) > 0$ for $v \neq \underline{v}$ (money below satiation) d) $s(\underline{v}) = s'(\underline{v}) = 0$ and e) $2s'(v) + vs'' > 0 \; \forall \; v \geq \underline{v}$ (money demand is finite and decreasing).

Households are less efficient than banks in managing capital holdings, inspired by the framework of Brunnermeier and Sannikov (2014). Following the shortcut of Gertler et al. (2020) we capture this via a term in the utility function, rather than explicitly modeling the precise reasons for why welfare is ultimately reduced or tracking an explicit resource loss. This term is given by

$$\Gamma(S_{H,t}, S_{CB,t}, S_t) \equiv \frac{\Theta_\Gamma}{2}\left(\frac{S_{H,t} + \Theta_{CB} S_{CB,t}}{S_t} - \gamma^F\right)^2 S_t \tag{7}$$

where $\Theta_Gamma > 0$, $\Theta_{CB} > 0$ and $\gamma^F > 0$. An increase in households' share in capital holdings increases the utility costs, but only once the combined share of security holdings of the household and the central bank $(S_{H,t} + \Theta_{CB} S_{CB,t})/S_t$ passes a threshold, γ^F.

Implicitly, it is assumed that the households are less effective in evaluating and monitoring capital projects and that after a threshold, this inferiority begins to tell. Expanding on this, one might envisage a certain fraction of firms being free from or less prone to, information frictions and which can be invested in effectively without monitoring expertize.

Similarly, we assume that the reallocation of securities away from commercial banks to the central bank also creates welfare costs. The parameter Θ_{CB} determines whether the welfare costs for the central bank are equal ($\Theta_{CB} = 1$), larger ($\Theta_{CB} > 1$) or lower ($\Theta_{CB} < 1$) relative to households holding the assets. Thus, we have a simple way of varying the efficiency of the central bank's portfolio, in terms of its impact on welfare.

Ultimately, this reduced form approach incorporates the realistic feature that non-expert holders of assets will require a price discount to assume the holdings of expert holders (in this case banks) *en masse* - which is the situation in the case of a run. A price discount will be applied in order to clear securities markets in the case of incumbent banks contributing to security demand. Indeed, it is this price discount that, in a run, *justifies* the run, by reducing the banks' ability to liquidate assets for sufficient funds to underpin the 'promised' return on deposits.

The optimality conditions for the money assets are given as

$$1 + \psi_m Ca_t = \beta E_t\left[\Lambda_{t,t+1}\Pi_{t+1}^{-1}\right] + \frac{\varphi_t}{\varrho_t}\left(\frac{M_t}{Ca_t}\right)^{\frac{1}{\eta_m}} \tag{8}$$

$$1 = \beta E_t\left[\Lambda_{t,t+1}\Pi_{t+1}^{-1}\right] R_{CB,t} + \frac{\varphi_t}{\varrho_t}\mu_{cb}\left(\frac{M_t}{D_{CB,t}}\right)^{\frac{1}{\eta_m}} \tag{9}$$

$$1 = \beta E_t\left[\Lambda_{t,t+1}\Pi_{t+1}^{-1} R_{t+1}\right] + \frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}} \tag{10}$$

where $\varrho_t = C_t^{-\sigma}/(1 + s(v_t) + s'(v_t)v_t)$ and $\varphi_t = s'(v_t)v_t^2\varrho_t$ are the Lagrange multipliers associated with the budget constraint and monetary aggregator respectively. As $\varphi_t/\varrho_t =$

$s'(v_t)v_t^2 = s_1(v_t^2 - s_2)$. s_1 governs the scale of the liquidity premia resulting from the transaction cost and s_2 sets the satiation point which we calibrate to be low so as to ensure satiation is never attained. The pricing kernel is $\Lambda_{t,t+1} \equiv \varrho_{t+1}/\varrho_t$. The last term in each equation refers to the liquidity premium associated with the specific asset. We define this liquidity premium term as $L_{Ca,t}$ for cash, $L_{CB,t}$ for CBDC, and $L_{D,t}$ for deposits.

The condition for households' optimal holdings of firm securities is

$$1 = \beta E_t \left[\Lambda_{t,t+1} \tilde{R}_{K,t+1} \right] \tag{11}$$

where an 'effective' return on capital for households is

$$\tilde{R}_{K,t+1} \equiv \frac{Z_{t+1} + (1-\delta)Q_{t+1}}{Q_t + \Gamma_1(S_{H,t}, S_{CB,t}, S_t)/\varrho_t}$$

The second term in the denominator of $\tilde{R}_{K,t+1}$ captures the aforementioned wedge in pricing that is positive if agents other than commercial banks hold an 'excessive' share of firm securities. A price discount will be applied in order to clear securities markets in the case of incumbent banks offloading their assets in the case of a run. Indeed, it is this price discount that, in a run equilibrium, justifies the run, as will be discussed below.

3.2. Production

There is a continuum of monopolistically competitive intermediate goods producers, producing output Y_t using labor L_t and capital K_t.[8] Their output is sold to a final goods producing firm, while capital is purchased from capital goods producers at Q_t. The intermediate goods production technology for firm f is given by

$$Y_t^f = A_t (K_{t-1}^f)^\alpha (L_t^f)^{1-\alpha} \tag{12}$$

A_t is total factor productivity, which follows an AR(1) process. The firm funds its capital purchases with the aforementioned securities. The securities offer a state-contingent return R_t^K, to be discussed further below when we describe the bank problem.

After using the capital in period t for production, the firm sells the undepreciated capital $(1-\delta)K_t$. The intermediate output is sold at a real price $\mathcal{M}_t$, which will be equal to marginal cost φ^{mc} at the optimum.

The final goods retailers buy intermediate goods and transform them using a CES

[8]We refer the reader to the online appendix for further formal details of the various optimization problems solved by firms.

production technology:

$$Y_t = \left[\int_0^1 (Y_t^f)^{\frac{\epsilon-1}{\epsilon}} df \right]^{\frac{\epsilon}{\epsilon-1}} \tag{13}$$

The associated price index and intermediate goods demand that emerge from this problem are given by:

$$P_t = \left[\int_0^1 (P_t^f)^{1-\epsilon} df \right]^{\frac{1}{1-\epsilon}}, \quad \text{and} \quad Y_t^f = \left(P_t^f / P_t \right)^{-\epsilon} Y_t \tag{14}$$

The final retailers' demand for intermediate goods define the demand curves faced by the intermediate good producers, who are subject to Rotemberg price adjustment costs.

Competitive capital goods producers produce new end-of-period capital using final goods. They create $\Gamma(I_t/S_{t-1})S_{t-1}$ new capital S_{t-1} out of an investment I_t. Thus, they solve

$$\max_{I_t} Q_t \Gamma \left(I_t/S_{t-1} \right) S_{t-1} - I_t \tag{15}$$

where $\Gamma(I_t/S_{t-1}) = a_1(I_t/S_{t-1})^{1-\eta_i} + a_2$. The resulting optimality condition defines a standard demand relation between the price Q_t and investment.

3.3. Banks

In equilibrium, banks' leverage depends on risk-shifting incentives and the possibility of a run. The banks' risk-shifting incentives, which are understood by depositors, endogenously limits their leverage and makes it depend on the level of volatility in the economy.

Banks can invest in two different securities with distinct risk profiles - one (idiosyncratically) safe and one risky. Limited liability protects the banks' in case of default and creates incentives to seek excessive risk from the depositors' perspective. This results in an incentive compatibility constraint featuring in the banks' problem. In order to obtain deposit funding that is only forthcoming if banks' behave 'appropriately', banks must continually satisfy this constraint. Since the incentive to renege increases with bank leverage and with the prevailing risk in the economy, the satisfaction of the incentive constraint manifests in state dependent leverage constraints that are tighter in riskier times.

Objective. There is a continuum of banks indexed by j, which intermediate funds between households and non-financial firms. They possess net worth, N_t^j, and collect deposits D_t^j to fund purchases of securities $S_t^{B,j}$ from intermediate goods producers. Leverage is defined as $\phi_t^j = Q_t S_t^{B,j} / N_t^j$.

The bank aims to maximize its franchise value, V_t, and, in the face of financial frictions, the decision over deposits and securities holdings is a joint one. The problem depends on the probability of a run because the bank can only continue operating or return its net worth to the household in the absence of a run. The probability of a run next period, conditional on t information, is denoted by p_t, which is endogenous and state-dependent. We defer the derivation of p_t to the next section. The value of the bank is then

$$V_t^j(N_t^j) = (1-p_t)E_t^{NR}\left[\Lambda_{t,t+1}\left(\theta V_{t+1}^j(N_{t+1}^j) + (1-\theta)(R_{t+1}^K Q_t S_t^{Bj} - R_{t+1}D_t^j)\right)\right] \quad (16)$$

where E_t^{NR} is the expectation conditional on no run in period $t+1$.

Since a run wipes out the bank's net worth, the continuation value in a run contingency is zero. The bank maximizes the franchise value subject to the incentive constraint resulting from the risk-shifting temptation, as now described. The bank must also satisfy a participation constraint ensuring that households provide deposits in positive quantities.[9]

Risk-Shifting Incentives and Volatility. We follow Christiano et al. (2014) in our design of the risk shifting problem. After purchasing securities, the bank converts them into efficiency units, ω_{t+1}, that are subject to an idiosyncratic shock, realized at the end of the period that is IID over time and banks. That is, the return earned by the bank is, $R_t^{Kj} = \omega_t^j R_t^K$. The bank can influence the distribution of this shock, following Adrian and Shin (2010) and Nuño and Thomas (2017). Specifically, it chooses between two options, which can be interpreted as choosing between investing in a good security and a bad security (or doing due diligence or not). In the 'good' case we assume the distribution of ω_t is degenerate, such that $\log \omega_t = 0$.[10] In the 'bad' case we have that

$$\log \omega_t \overset{iid}{\sim} N\left(\frac{-\sigma_t^2 - \psi}{2}, \sigma_t\right), \quad (17)$$

where $\psi < 1$. σ_t, which affects the idiosyncratic volatility, is an exogenous driver of risk, to be specified shortly. The 'bad' security follows a conditionally log normal distribution, where $F_t(\omega_t)$ is the cumulative distribution function. The good security's intrinsic superiority is reflected in its higher mean *and* lower variance. However, the substandard security features a higher upside risk: a high realization of the idiosyncratic shock results in a large return on assets. Given that the banks possess limited liability, the optionality provides them with an incentive to gamble for this upside.[11]

Variation in σ_t affects the relative cross-sectional idiosyncratic volatility of the securities. In particular, it changes upside risk, while preserving the mean spread between the

[9]The derivation of the contracting problem is discussed in Appendix C.

[10]For simplicity, we abstract from idiosyncratic volatility for the good security to emphasize the essential element, which is the *difference* in risks between the two options.

[11]$1 > e^{-\frac{\psi}{2}}$ and $0 < [e^{\sigma^2} - 1]e^{-\psi}$, where we recall $\psi < 1$

good and bad options. We posit that σ_t evolves exogenously, following an AR(1) process:

$$\sigma_t = (1 - \rho^\sigma)\sigma + \rho^\sigma \sigma_{t-1} + \sigma^\sigma \epsilon_t^\sigma, \tag{18}$$

where $\epsilon_t^\sigma \sim N(0,1)$. Given our assumptions, the bank earns the aggregate return R_t^K on its securities if it chooses the 'good' option, where $R_t^K \equiv \frac{(1-\delta)Q_t+Z_t}{Q_{t-1}}$. If the bank chooses the bad option, there is an additional source of idiosyncratic risk due to the non-degenerate distribution of ω_t^j. Thus, a threshold value $\overline{\omega}_t^j$ for the idiosyncratic shock defines when the bank can exactly cover the face value of the deposits:

$$\overline{\omega}_t^j = \frac{\bar{R}_{t-1}^D D_{t-1}^j}{R_t^K Q_{t-1} S_{t-1}^{Bj}}. \tag{19}$$

Note that the threshold is state-dependent, due to 'systemic' risk arising from the randomness of R_t^K.

Were it not for limited liability, banks would invest in the good security. However, limited liability distorts the choice between the securities and creates risk-shifting incentives. If the realized idiosyncratic volatility is below $\overline{\omega}_t^j$, the bank declares bankruptcy. Households then seize all the bank's assets, which are valued less than the promised repayment. This limits the downside risk to the bank of the substandard security, while the upside benefit is unaffected. The gain to the bank from investing in the substandard technology is:

$$\tilde{\pi}_t^j = \int^{\overline{\omega}_{t+1}^j} (\overline{\omega}_{t+1}^j - \tilde{\omega}) dF_t(\tilde{\omega}) > 0. \tag{20}$$

In contrast, there is no such gain from optionality in the case of the good security.

An incentive constraint ensures that the good security is chosen in equilibrium. This constraint manifests in the bank maintaining enough 'skin in the game' - that is, partly funding its investments with its own net worth. Leverage is therefore limited since the risk shifting incentive of the upside gain is increasing in leverage. Formally, we obtain the following incentive constraint (associated with Lagrange multiplier, κ_t)

$$\begin{aligned}(1-p_t)E_t^{NR}\left[\Lambda_{t,t+1}R_{t+1}^K(\theta\lambda_{t+1}^j(1-L_{D,t+1})+1-\theta)(1-e^{\frac{-\psi}{2}}-\tilde{\pi}_{t+1}^j)\right] \\ = p_t E_t^R\left[\Lambda_{t,t+1}R_{t+1}^K(e^{-\frac{\psi}{2}}-\overline{\omega}_{t+1}^j+\tilde{\pi}_{t+1}^j)\right]\end{aligned} \tag{21}$$

for which the derivations are found in the online appendix. The LHS illustrates the trade-off between the higher mean return of the 'good' security and the upside risk of the bad.

There is an additional gain of investing in the substandard security in case of a run, which is reflected in the RHS term: the bad security offers the chance of surviving a run.

If $\omega_t^i > \overline{\omega}_t$, the bank can repay its depositors because of an 'unexpectedly' high payoff to the bad security. Investing in substandard securities, however, remains an off-equilibrium strategy.

In addition to the incentive constraint, the banker must also satisfy a participation constraint for households to supply deposits, with which we associate the Lagrange multiplier, λ_t. Both constraints are assumed to be binding in equilibrium.

Aggregation. The banks' constraints do not depend on bank-specific characteristics. Thus, the optimal choice of leverage is independent of net worth. Therefore, we can sum across individual banks to obtain equilibrium conditions in terms of aggregate values. Banks' aggregate demand for assets depends on leverage and net worth ($Q_t S_t^B = \phi_t N_t$).

In the absence of a run, incumbent banks retain their earnings. However, a run eradicates the net worth of the incumbent banks and they stop operating. Additionally, *new* banks, which are equipped with a transfer from households, enter in each period, regardless of whether a run takes place or not:

$$N_{S,t} = \max\{R_t^K Q_t S_{t-1}^B - R_t^D \Pi_t^{-1} D_t, 0\}, \qquad \text{and} \qquad N_{N,t} = (1-\theta)\zeta S_{t-1}, \tag{22}$$

where $N_{S,t}$ and $N_{N,t}$ are the net worth of incumbent and new banks, respectively.

Endogenous runs and multiple equilibria. There are occasional runs on the banking sector, in which depositors stop rolling over their deposits at incumbent banks. Importantly, the probability of a run is endogenous because the existence of a run equilibrium depends on economic circumstances, following Rottner (2023) and Gertler et al. (2020). Conditional on a run equilibrium existing, we face a situation of multiple equilibria, in the spirit of Diamond and Dybvig (1983).

During normal times households roll over their deposits. Banks and households both demand securities and the market clears at a 'fundamental' price. That is, a price where the bank can cover the promised repayments *given* Q_t. In contrast, a run wipes out the entire *existing* banking sector ($N_{S,t} = 0$). This leaves only households, the central banks, and the newly entering banks (who are quantitatively small and constrained) demanding securities. Consequently, the asset price falls to clear the market at a firesale price. The drop is particularly severe because it is costly for households to hold large amounts of securities, as discussed above.

The firesale price $Q_t^\star$ is so low as to imply a liquidation value of banks' securities below that which would allow them to pay the promised return to depositors - thus justifying the run in the first place. $Q_t^\star$ is such that the recovery ratio *conditional on a run*, denoted $x_t^\star$, is below 1:

$$x_t^\star \equiv \frac{[(1-\delta)Q_t^\star + Z_t^\star]S_{t-1}^B}{\bar{R}_{t-1} D_{t-1}} < 1. \tag{23}$$

The variable $x_t^\star$ partitions the state space into a safe region without runs ($x_t^\star \geq 1$) and a fragile region with multiple equilibria ($x_t^\star < 1$). Note that a run may not occur even if $x_t^\star < 1$.

In the safe region, where $x_t^\star \geq 1$, banks can cover the claims under the fundamental *and* firesale price. Therefore, runs are not possible and only the normal equilibrium exists. In contrast, both equilibria exist in the fragile region where the banks have sufficient means to repay depositors *only under the fundamental price*. Conditional on the economy being in the fragile region, a sunspot shock selects the equilibrium, following Cole and Kehoe (2000). The sunspot shock ι signals 'run' with probability Υ and 'no run' with probability $1-\Upsilon$. If it signals run *and* $x_t^\star < 1$, a run takes place.

Thus, the probability for a run in period $t+1$ depends on the probability of being in the crisis region in the next period and of drawing the 'run' realization of the sunspot shock: $p_t = \text{prob}(x_{t+1}^\star < 1)\Upsilon$. The run probability is time-varying and endogenous, as $x_{t+1}^\star$ depends on the macroeconomic and financial circumstances.

3.4. Government, monetary authority and closing the Model

We here describe the actions of monetary and fiscal authorities, which could follow a number of different policies.

3.4.1. Government

The government period budget constraint is given by

$$G + \frac{R_{I,t-1}}{\Pi_t} B_{t-1} = T_t + B_t + T_{CB,t} \tag{24}$$

where G denotes government spending, T_t captures lump sum transfers from households, and $T_{CB,t}$ is remittances from the central bank to the government. We assume that government spending G is constant and that bonds are in zero-net supply. Thus we have that $G = T_t + T_{CB,t}$. Thus, remittances are used simply to reduce lump sum taxation.

3.4.2. Monetary authority

The central bank issues liabilities (cash and CBDC), purchases assets, and operates with net worth. We assume that the central bank uses the funds from money issuance to purchase securities issued by firms at the market price[12]

$$Q_t S_{CB,t} = Ca_t + D_{CB,t} + N_{CB,t} \tag{25}$$

In fact, we assume that all net income is rebated to the government each period, implying constant net worth. We set $N_{CB,t}$ to be constant at zero though the particular value, in

[12]Either directly, or through a private (unmodeled) mutual fund. Jackson and Pennacchi (2021) evaluate different ways of using funds from CBDC issuance.

our model, is unimportant (see Del Negro and Sims (2015) for important discussions of central bank balance sheets and their place in the fiscal framework).

An important element is how effectively the central bank invests relative to households. As implied in our earlier discussions, we assert a utility loss arising from either households or the central bank investing directly in securities (recall equation (7)). We introduce the parameter Θ_{CB} to parsimoniously capture different possibilities. When both central bank and households are equally (in)efficient ($\Theta_{CB} = 1$), the equilibrium is unaffected by a shift in investment portfolio from central bank to household i.e. if the central bank rebates lump-sum the funds from liability issuance to households.[13] We consider this our baseline calibration.

In contrast, when the central bank has investment superiority to households (but not necessarily to banks), $\Theta_{CB} < 1$, we can capture an asset-price support channel which is increasing in the quantity of CBDC (and cash) issued. In a run, household funds that flow to CBDC (or cash) can be reinvested with lower welfare loss by the central bank, than had households invested directly in securities themselves. Consequently, the central bank can purchase more securities relative to the household, and asset prices fall less far. The converse holds when $\Theta_{CB} > 1$.

An alternative option would have been to assume that the central bank can invest in private bank deposits, denoted, $D_{B,t}$, as envisioned in Brunnermeier and Niepelt (2019). Of course, provided the central bank can reinvest deposits instantaneously (and there is no capital flight to non-CBDC accounts), such a policy would prevent equilibrium runs completely. Naturally, there are significant practical complications with this proposal, not least which banks to invest in and under what terms. As Brunnermeier and Niepelt (2019), their results provide stylized benchmarks for conditions where various policies are 'equivalent' in theory, but where in reality other frictions and political constraints could complicate matters. Moreover, if such a policy were anticipated *ex ante*, it could engender significant moral hazard. Even if such recycling of funds were a reasonable policy option, one could appeal to a model such as ours as a way of assessing costs of *not* pursuing it - perhaps to unlock 'congressional approval' for emergency actions.

3.4.3. Monetary policy

The monetary authority follows a standard Taylor Rule for setting the nominal interest rate $R_{I,t}$.

$$R_{I,t} = \max\left[R_I\left(\frac{\Pi_t}{\Pi}\right)^{\kappa_\Pi}\left(\frac{\varphi_t^{mc}}{\varphi^{mc}}\right)^{\kappa_y}, R^{LB}\right], \tag{26}$$

[13] We also require that $S_{H,t} > S_{CB,t}$ always holds in equilibrium, which we verify numerically in our simulations.

where φ^{mc} is the deviation of marginal costs from steady state. We explicitly acknowledge a zero lower bound constraint imposed by the zero lower bound.

The government may issue one-period nominally riskless bonds, which must necessarily pay the riskless nominal rate $R_{I,t}$ by no-arbitrage. While we assume that government bonds will be in zero net supply – and hence were not explicitly acknowledged in the household budget constraint, (3) – the associated Euler equation for households is

$$1 = \beta E_t \left[\Lambda_{t,t+1}\Pi_{t+1}^{-1}R_{I,t}\right] \tag{27}$$

Combining this expression with the Euler equation for balances of CBDC, we obtain a relationship between $R_{I,t}$, $R_{CB,t}$ and $D_{CB,t}$. If CBDC policy is implemented through choosing its rate of remuneration, $R_{I,t}$, then the central bank is assumed to supply whatever amount of CBDC is necessary to ensure the above condition holds. If, instead, the central bank controls the supply of CBDC as its intermediate policy target, then the rate of remuneration must adjust.[14]

3.4.4. Closing the model

The aggregate resource constraint is

$$Y_t = (1+s_t)C_t + I_t + G_t + \frac{\psi_m}{2}Ca_t^2 + \frac{\rho^r}{2}\left(\frac{\Pi_t}{\Pi} - 1\right)^2 Y_t, \tag{28}$$

where the penultimate term is the holding cost of cash and the last term captures the adjustment costs from Rotemberg pricing.

4. Model Parameterization and Global Solution Method

In this section, we explain how we map the model to the data and how we parameterize the demand for CBDC exploiting our survey. We also outline our global solution method that accounts fully for endogenous runs and other nonlinear features such as the zero lower bound. We calibrate the model to the euro area using quarterly data from 2000:Q1 to 2023:Q4, supplemented with our survey on German households. As aforementioned, We emphasize the qualitative takeaways from the survey's questions on bank distress contexts, while making use of quantitative predictions from questions related to CBDC demand in normal times.

[14] In our baseline case, we assume that CBDC is unremunerated, $R_{CB,t} = 1$. However, for equation to hold, we need to have that $R_{I,t} > 1, \forall t$. For this reason, we need to set the lower bound, R_{LB}, to a value that is above 1. If the policy rate is at 1 or below, that is $R_{I,t} \leq 1$, the model would not be determinate. An alternative could be to introduce a remunerated CBDC, which we consider later in the paper.

4.1. Mapping Model to the Data

The parameters can be divided into conventional parameters, parameters related to money holdings, and parameters governing the banks. Table 2 summarizes the parameterization, sources, and chosen data moments.

β is set to 0.995, yielding a 2% real interest rate. The risk aversion is set for logarithmic utility, while the Frisch labor elasticity is 0.75. We normalize the TFP level to target an average output of 1 and the labor disutility χ parameter is set to 1. We set government spending to match its ratio to GDP of 0.2. The capital share α is 0.33 and the depreciation rate δ is 0.025, which are typical values accepted in the literature. For the price elasticity ϵ and the Rotemberg adjustment costs ρ^r, we choose $\epsilon = 10$ and $\rho^r = 178$ (corresponding to a Calvo duration of 5 quarters) – again, values in line with the literature. The investment elasticity follows Bernanke et al. (1999) while the other parameters of the investment function are set so that the asset price is normalized to 1 and that $\Gamma(I/K) = I$ holds approximately at the deterministic steady state. The central bank targets an inflation rate of 2%, while the responses to inflation and the output gap are conventional with $\kappa_\pi = 1.5$ and $\kappa_y = 0.2$.

The next step is to parameterize the money holdings, transaction costs and storage costs. We set the transaction cost parameter s_1 to target currency in circulation, which is around 45% of quarterly GDP (in the economy without CBDC). When households hold cash, they face storage costs ψ_m, which we set to 0.002 in line with Burlon et al. (2024). The different types of money are imperfectly substitutable, and we set η_m to 6.6 based on Di Tella and Kurlat (2021). While their study focuses only on cash and deposits, we assume the same elasticity also for CBDC following Abad et al. (2025). We set the second parameter, s_2, to the low value of 10^{-4} to ensure that liquidity premia are low when money-holdings are high (as in a run) and yet non-zero – to avoid satiation in money-holdings. This has the additional effect of containing somewhat the increase in cash holdings during a run. We set the weight for deposits μ_d to target a spread between the policy rate and deposit rate of approximately 75 basis points in annual terms.

To understand the implications of CBDC, it is important to calibrate the demand for CBDC - something which is difficult, given its real world absence. Our strategy is to exploit our survey to calibrate a baseline scenario (based on all respondents) and an optimistic scenario (based on 'keen' respondents, as defined in section 2). The survey suggests an average CBDC to cash ratio of 0.66 in normal times, which we take as our baseline. We target this ratio in the risky steady state (RSS) setting μ_{cb} to approximately 0.89.[15] Under the optimistic scenario, we target a ratio of 1.40 - the average ratio of

[15]The economy converges to the risky steady state when agents *expect* the materialization of shocks according to their probability law but, over a long period, the shocks nevertheless *do not* materialize (see Coeurdacier et al. (2011)). In contrast to the deterministic steady state, it incorporates agents' knowledge of the shock process.

CBDC-to-cash among the 'Keen'. As mentioned in the survey section, this scenario might arguably be seen as more reflective of take-up after more extensive marketing of d€ and greater familiarity. Finally, to encompass other uptake scenarios, we provide robustness analysis by varying the parameter μ_{cb}.

The last set of parameters relates to the banking sector. We use the asset share of households to target that approximately one-third of assets are runnable. We aim for a leverage ratio of around 15.5, by setting the mean of the substandard security. The intermediation cost of households is set to match an average credit spread. The standard deviation of the volatility shock targets the frequency of a financial crisis. In line with the macrohistory database of Jordà et al. (2017), albeit at the lower end, we target that a run occurs on average every 75 years. The persistence of the volatility shock and the survival rate are set following Rottner (2023). The parameter calibrating the initial net worth of new banks ζ follows from setting the other parameters. The specification of the sunspot shock targets an average drop of around 2% (8%) during a run period.

4.2. Global Solution Method

We solve the model using global solution methods. This allows us to fully account for key – and highly nonlinear – features: endogenous runs and occasionally binding constraints. As such, the impact of CBDC on both the macroeconomy and financial stability in normal times (*slow disintermediation*) and through its influence on runs (*fast disintermediation*) can be jointly analyzed within a single medium-scale macroeconomic model.

The solution method is time iteration with piecewise linear policy functions as in Richter et al. (2014), which is adapted to incorporate endogenous runs following Rottner (2023). In addition to the endogenous runs, the method also accounts for the occasionally binding zero lower bound and potential holdings limits of CBDC. In total, the model features 4 state variables $\mathbb{X} = \{S, N, \sigma, \iota\}$ in a setup with multiple equilibria and occasionally binding constraints. Due to the existence of multiple equilibria, we characterize our policy functions as consisting of two parts, where each part describes either the normal or the run equilibrium, respectively. Appendix E contains the details on the numerical solution procedure.

5. Results

We first demonstrate the run propagation dynamics in our model and highlight the dynamics of CBDC holdings during such episodes. We then disentangle the main channels through which CBDC affects slow and fast disintermediation under different assumptions regarding CBDC demand and in the absence and presence of holding limits.

Parameters		Value	Target / Source
a) Conventional parameters			
Discount factor	β	.995	Risk free rate = 2.0% p.a.
Frisch labor elasticity	$1/\varphi$	.75	Conventional
Risk aversion	σ^H	1	Logarithmic utility function
TFP level	A	.407	Output normalization
Labor disutility	χ	1	Normalization
Government spending	G	.2	Govt. spending to GDP ratio
Capital share	α	.33	Capital income share
Capital depreciation	δ	.025	Depreciation rate
Price elasticity of demand	ϵ	10	Markup
Rotemberg adjustment costs	ρ^r	178	Calvo duration of 5 quarters
Elasticity of asset price	η_i	.25	Bernanke et al. (1999)
Investment parameter 1	a_1	.530	Asset price normalization
Investment parameter 2	a_2	$-.008$	Investment normalization
Target inflation	Π	1.005	ECB's inflation target
Monetary policy response to inflation	κ_π	1.5	Literature
Monetary policy response to output gap	κ_y	.125	Literature
b) Parameters related to money			
Transaction cost scale	s_1	.04	Currency to GDP ratio
Transaction satiation	s_2	10^{-4}	Unsatiated demand
Cash storage cost	ψ_m	.002	Burlon et al. (2024)
CES elasticity	η_m	6.6	Di Tella and Kurlat (2021)
Deposit weight	μ_d	.21	Spread policy and deposit rate
CBDC weight: baseline	μ_{cb}	.89	Conducted household survey
CBDC weight: keen	μ_{cb}	1.01	Conducted household survey
c) Banking sector & shocks			
HH asset share cost	γ^F	.33	Share of runnable assets
Mean substandard security	ψ	.01	Bank capital level
HH intermediation cost	Θ	.04	Credit spread
Survival rate	θ	.88	Rottner (2023)
Persistence volatility	ρ^σ	.96	Rottner (2023)
Std. volatility shock	σ^σ	.001	Financial crisis probability
Sunspot Shock	Υ	.50	GDP response during run

Table 2: Calibration and Targeted Moments

5.1. Endogenous runs and the role of CBDC

Figure 4 shows the response of the economy to a sequence of volatility shocks. The economy is initially at the risky steady state and the sequence of shocks is designed to show the dangers of a period of 'calm', followed by a trigger that opens up scope for a run. As such, we echo patterns observed prior to the Great Financial Crisis: a credit boom and elevated leverage as observed around 2008, reflecting a 'volatility paradox' where calm times sow the seeds of later crises (see Adrian and Shin (2010) and Brunnermeier

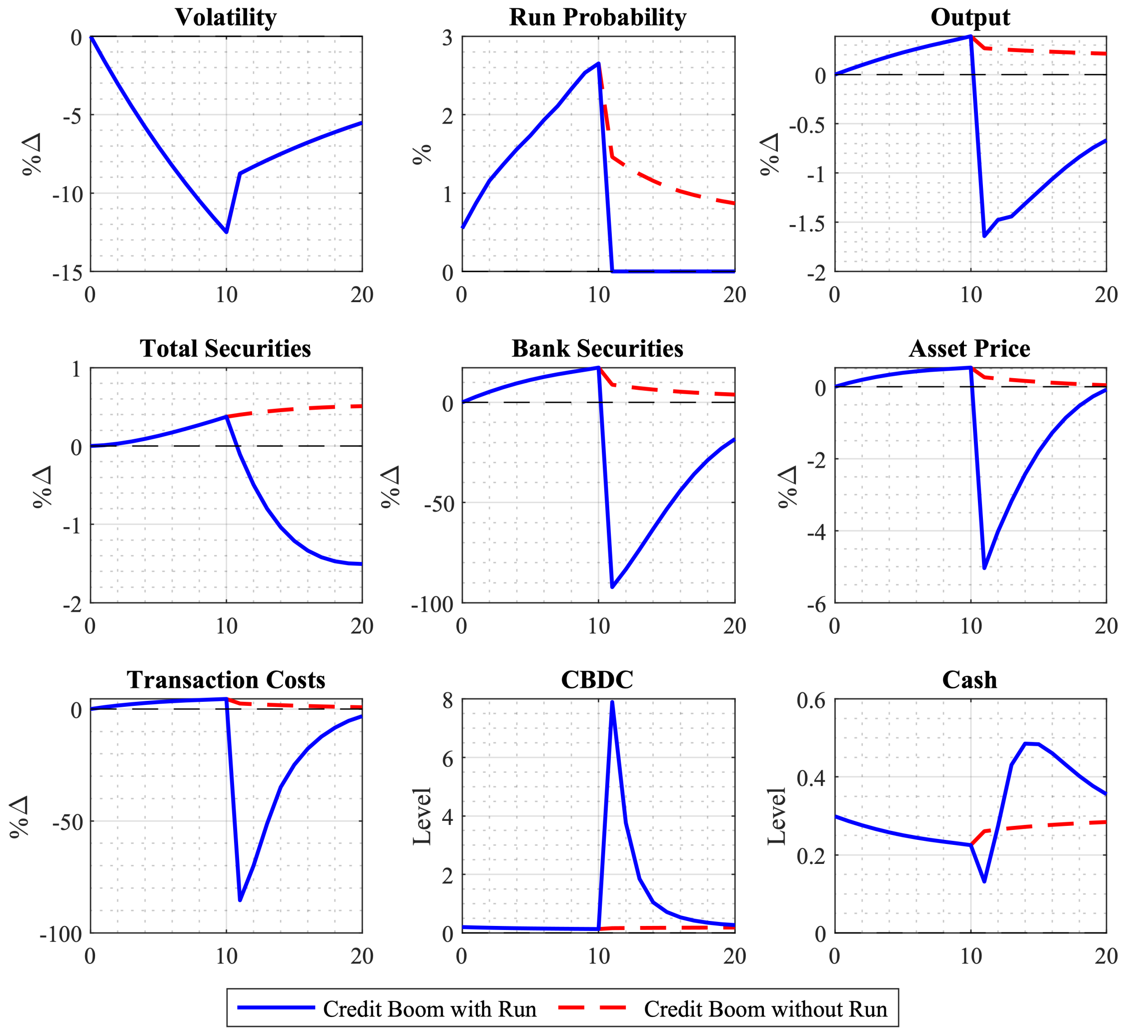

Figure 4: Impulse response of the economy to a sequence of volatility shocks. We show both possible cases: a boom with a run (blue solid line); and a boom without a run (red dashed line). The scales are either percentage deviations from the risky steady state (%Δ), annualized percent (% (p.a.)), percent (%), or in levels.

and Sannikov (2014)).

Formally, we draw a sequence of one-standard-deviation *negative* volatility shocks for the first two and half years (10 quarters), followed directly by a two-standard-deviation *positive* volatility shock. The period of low volatility induces a 'credit boom' (substantial asset growth in the banking sector) and high leverage (since lower volatility reduces the risk-shifting incentives). The realization of high volatility pushes the highly levered economy into the fragile region of multiple equilibria. The recovery ratio (return from liquidating the balance sheet relative to promised repayments) falls below 1, reflecting the fact that in this high volatility state, were a run to occur, the newborn banks would be particularly constrained in their ability to fund firms, leaving a heavy load for households and necessitating a severe asset price decline. The sunspot shock selects either the run equilibrium or the equilibrium without run.

In figure 4, we see the evolution of the economy both with and without the materialization of a run. Our focus is the former. Bank securities and deposits drop precipitously as the run occurs. All else equal, this necessitates a large increase in the holdings of securities by either households or the central bank, or both.

As banks retreat, households will only hold securities at a discount, which leads excess returns to spike and investment (and thus output) to collapse. At the same time, we see a large increase in CBDC holdings which offer safety and importantly storage at scale (no storage costs), highlighting the threat of 'fast' disintermediation. CBDC demand is sufficiently high that there is a temporary fall in cash holdings as households' liquidity demands are met by the CBDC (note the fall in transaction costs), setting aside its safety benefits. This effect reverses as the crisis abates and CBDC attractiveness falls.

Figure 5 compares these dynamics to an economy *without* CBDC. This comparison shows that CBDC has a negative impact on financial stability through increasing the probability of a run - CBDC enhances 'fast' disintermediation. While in the economy without CBDC, households *do* run to cash, the magnitude is substantially smaller than the run to CBDC. This is connected to the less dramatic erosion of banks' liquidity premium in the cash case.

This disintermediating tendency of CBDC also operates in 'normal times' and induces 'slow disintermediation'. We will discuss this further below, but the diagram does reflect it to some extent. In the *pre-run* periods, note that the overall level of securities is higher in the absence of CBDC. Given the dominant role of banks in holding these securities in normal times, this partly reflects a larger banking system. Associated with this, we also can observe (prior to the run) a more generous liquidity premium for banks in the absence of CBDC, as captured in the spread between the deposit rate and the policy rate. In the absence of CBDC banks pay lower deposit rates, relative to the policy rate. In the next section, we disentangle the influences of CBDC design choices on 'slow' and 'fast' disintermediation.

We should acknowledge the limitation of our model in that we do not simultaneously match survey-implied cash and d€ demand in both 'normal times' *and* in times of bank stress. In our model, due to the shift towards CBDC, cash demand declines as the household's demand for liquidity is sated by CBDC. This is not what we observe in our survey. Indeed, in the survey, there appears to be a tendency for people to run predominantly to cash, even if that tendency is substantively reduced in the presence of CBDC.

Presumably, current familiarity with cash contributes a substantial boost to its demand. This plausibly will subside in the near future - in line with reduced cash transactions - and with increased experience with digital money in general, and d€ in particular. We also acknowledge the idiosyncrasies of German households in this respect, given their

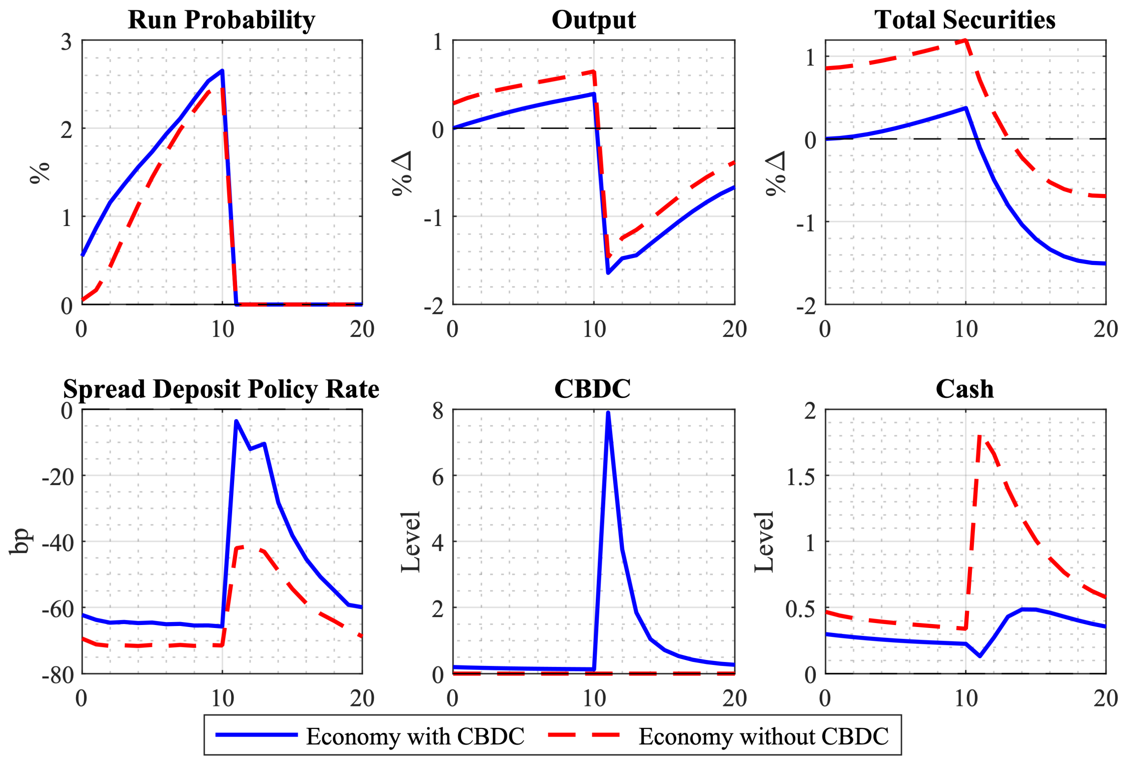

Figure 5: Comparison between an economy with CBDC (blue solid) and without CBDC (red dashed) during a credit boom gone bust. The sequence of shock is the same as in figure 4. The scales are either percentage deviations from the risky SS from the economy with CBDC (%Δ), annualized percent (%), annualized basis points (bp), or level.

unusual (relative to nearby European countries) affinity for cash.[16]

5.2. Slow and Fast Disintermediation

To disentangle the channels through which CBDC affects the economy, we compare different setups. Specifically, table 3 reports how design choices for the monetary system affect financial stability and other economic outcomes, along with household welfare, expressed in consumption equivalents.

We emphasise two channels: the 'liquidity premium channel' of CBDC and the 'storage at scale channel'. The first is inextricably linked with slow disintermediation. The introduction of CBDC reduces the demand for deposits, as it is partially substitutable as an alternative means of payment. Consequently, the liquidity premium that banks earn from offering deposits is reduced. This has two opposing effects on financial stability that are connected to 'slow' and 'fast' disintermediation. As banks enjoy a lower liquidity premium in normal times, the size of the financial sector is correspondingly smaller.

Since the banking sector is fragile, due to the primitive frictions leading to risk shifting problems, this mechanism *enhances* stability via 'slow' disintermediation. However,

[16]One might consider adding a preference shifter in favor of non-digital assets in times of runs, to help match the data. But, of course, this would be rather mechanical - though not without some plausibility.

during the turbulent times of a run, the 'liquidity premium channel' works against financial stability. The liquidity premium of newly emerging banks is also smaller in a crisis, which reduces their capacity to receive cheap funding and help to stabilize the financial system. Therefore, banks have a harder time attracting deposits during a run and in its aftermath.

To quantify these forces, table 3 compares deposit holdings and the liquidity premium that banks have for deposits in the CBDC economy (column 1) and non-CBDC economy (column 2). To evaluate the impact on 'slow' disintermediation, it is appropriate to compare values in the respective risky steady states. Deposit holdings and liquidity premium (measured as the spread between the deposit rate and the policy rate) are smaller for the CBDC economy, by approximately 6 basis points. Furthermore, we can observe that the banking sector holds fewer assets and has a slightly smaller share in the economy - patterns that were also in evidence in figure 5.

We refer to the second channel as the 'storage at scale channel' of CBDC. There is arguably no technological constraint that prevents scaling up of CBDC holdings, which is an important difference from cash. While the role of storage costs is second-order in normal times and has only a negligible impact on 'slow' disintermediation, this issue is at the forefront when considering 'fast' disintermediation. When comparing the behavior of households in a run in a CBDC and non-CBDC world, we observe that households move much larger sums into CBDC compared to cash in a non-CBDC world. In fact, we observe that the CBDC holdings are four times greater than cash holdings in a run. The CBDC's 'storage at scale' property puts pressure on the newborn banks ability to fund themselves, increasing the reliance on households (or the central bank) to fund firms. All else equal, this requires a more substantial asset price drop, which underpins the greater vulnerability of the economy to fast disintermediation.

It is important to note that the two channels oppose each other in terms of their effects on financial stability. It then becomes a quantitative question, which is dominant - the 'liquidity premium channel' that primarily drives slow disintermediation, or the 'storage at scale channel' that primarily drives fast disintermediation. When comparing the impact of introducing CBDC on welfare and financial stability, it turns out that the economy is worse off on introducing CBDC because of the 'storage at cost channel' (and, thus, fast disintermediation dominates). Welfare is 0.13% higher in the absence of CBDC, measured in consumption equivalents. Furthermore, the probability of observing a run is almost 50% lower (1.34% vs 2.46%) in the absence of CBDC. In other words, a run occurs on average every 75 years, rather than every 40 years.

To better understand the relevance of these channels to assessing the possible impact of introducing CBDC, it is helpful to consider different parameterizations. Based on the keen respondents to our survey, we consider a scenario with $\mu_{cb} = 1.01$. That is, we increase the weight of CBDC in the money aggregator, matching the higher implied

	Base $\mu_{cb} = 0.89$	No CBDC $\mu_{cb} = 0$	Keen $\mu_{CB} = 1.01$	Holding limit $\overline{D}_{CB} = 0.17$	Remuneration $R_{CB,t}$
Key moments					
Welfare W (CE)[a]	–	0.13	0.04	0.16	0.20
Run probability[b]	2.46	1.34	2.10	1.16	0.92
Risky steady state[c]					
CBDC D_{CB}	0.20	0	0.30	0.17	0.21
Cash Ca	0.30	0.47	0.21	0.32	29
Deposit D	3.51	3.53	3.47	3.49	3.48
Money M	1.24	1.17	1.29	1.23	1.24
Transaction cost $s(v)$	1.77%	1.88%	1.71%	1.79%	1.78%
Spread $R_D - R_I$ (bp)	−62.3	−69.4	−57.8	−63.2	−62.1
Total Securities S	9.06	9.14	9.04	9.10	9.10
Share Banks S_B/S	41.4%	41.3%	41.0%	40.9%	40.8%
Average value during run period[d]					
CBDC D_{CB}	7.73	0	7.22	0.17	0.00
Cash Ca	0.13	1.832	0.11	1.68	1.83
Deposit D	0.23	0.25	0.23	0.24	0.25
Money M	7.10	1.92	7.64	2.02	1.92
Transaction cost $s(v)$	0.3%	1.1%	0.2%	1.1%	1.1%
Spread $R_D - R_I$ (bp)	0.0	−0.1	0.0	−0.1	−0.1
Average (non-run and run periods)[e]					
CBDC D_{CB}	0.33	0	0.40	0.17	0.21
Cash Ca	0.30	0.49	0.22	0.35	0.32
Deposit D	3.32	3.42	3.31	3.40	3.40
Money M	1.33	1.18	1.37	1.24	1.25
Transaction cost $s(v)$	1.74%	1.87%	1.68%	1.78%	1.76%
Spread $R_D - R_I$ (bp)	−61.1	−69.3	−57.1	−63.6	−62.4
Total Securities S	8.99	9.09	8.98	9.06	9.06
Share Banks S_B/S	39.4%	40.2%	39.3%	40.0%	40.1%

[a] Welfare change expressed as consumption equivalent relative to baseline CBDC (%).
[b] Annual run probability (%).
[c] The risky state level of the variables is shown. The spread for $R_D - R_I$ is expressed in annualized basis points (bp).
[d] Displayed value is the average of all observed runs in our simulation (100000 periods). The spread for $R_D - R_I$ is expressed in annualized basis points (bp).
[e] The average value over the entire simulation of 100000 periods is displayed.

Table 3: Welfare, financial stability and economic outcomes of various policies

demand for CBDC, relative to cash. This essentially only affects the 'liquidity premium channel' and, thus, slow disintermediation. As shown in column 3 in the table, welfare, and financial stability improve in this scenario relative to our baseline. However, a non-CBDC world is still better, according to the model, because the 'fast' disintermediation

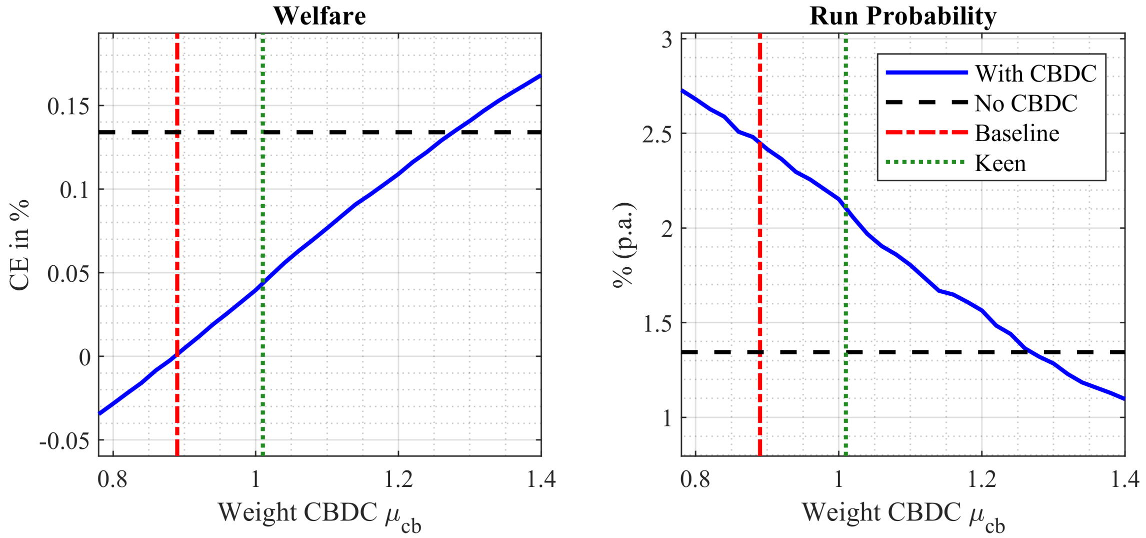

Figure 6: Impact of variations in the weight of CBDC μ_{cb} in the money aggregator on the equilibrium (blue line). Baseline scenario (red dash-solid), keen scenario (green footed) and no CBDC scenario (black dashed) are highlighted. The scales are either consumption equivalent in percent (CE in %), or annualized percent (% p.a.).

threat still dominates.

5.3. Demand for CBDC: Welfare, financial stability and economic consequences

Our baseline and keen parameterizations both suggest that the introduction of CBDC reduces financial stability and, thus, lowers welfare. However, given uncertainty over CBDC adoption we explore how varying μ_{cb} over a broader range of values affects the results.

We find that welfare gains increase with μ_{cb}. Higher demand for CBDC enhances 'slow' disintermediation via the 'liquidity premium channel', in addition to higher values of μ_{cb} capturing a benefit of superior 'money' (implicit in the higher demand for it). The 'storage at scale channel' is unaffected by changes in how useful CBDC is as a means of payment - it relates to CBDC storage which, as noted previously, is key in run times. Indeed, as shown in figure 6, the introduction of CBDC can have positive welfare effects for sufficiently high values of μ_{cb}, though these would imply 'counterfactually' high preference for CBDC. The figure shows that introducing CBDC becomes welfare-improving at a level of $\mu_{cb} = 1.28$. Such a value implies a demand for CBDC that is double that in our baseline parameterization and 1.5 times that of our keen parametrization, as shown in Appendix G in detail.

While the more extreme values of μ_{cb} and CBDC demand that they imply are likely counterfactual at this point, it is worth considering what they suggest for the evolution of digital moneys in the future. In many economies, cash use is clearly in decline and comfort with digital money is rapidly increasing. In the particular case of Germany, where our survey took place, there is obvious scope for an increase in the use of digital money, from a relatively low base.

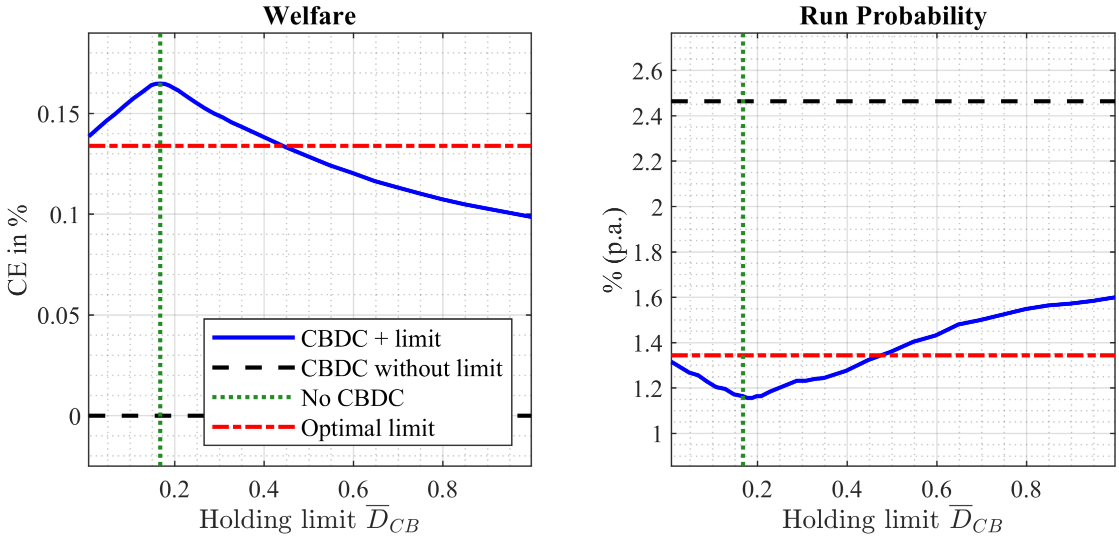

Figure 7: Impact of holding limits for CBDC $\overline{D}_{CB}$ on the equilibrium (blue line) for the base scenario $\mu_{cb} = 0.89$. The horizontal lines show CBDC without limit (black dashed) and the economy without CBDC for comparison. Most variables display their mean. CBDC-cash-ratio and CBDC values are shown for the risky steady state value The scales are either consumption equivalent in percent ($CEin\%$), annualized percent (% p.a.), level or basis points for annualized spread (bp).

6. Design of CBDC

In this section we consider two of the most discussed design choices for CBDC: holding limits (for unremunerated CBDC) and remuneration.

6.1. Holding Limits

It has been commonly suggested that there should be a limit on how much CBDC can be held. Frequently, the argument is motivated by concerns of 'fast disintermediation'. As such, we now complement our earlier specification of (unremunerated) CBDC now with a holding limit $\overline{D}_{CB}$. Such a limit alters the households' maximization problem as they now face the following additional constraint: $D_{CB,t} \leq \overline{D}_{CB}$ The first order condition that determines the CBDC demand, equation (9) originally, now becomes

$$1 + \overline{\mu}_{CB,t} = \beta E_t \left[\Lambda_{t,t+1} \Pi_{t+1}^{-1} \right] R_{CB,t} + \frac{\varphi_t}{\varrho_t} \mu_{cb} \left(\frac{M_t}{D_{CB,t}} \right)^{\frac{1}{\eta_m}} \tag{29}$$

where $\overline{\mu}_{CB,t}$ is the normalized multiplier associated with the new constraint. In the equilibria and parameterization we consider it *will* occasionally bind.

Clearly, holding limits constrain the 'storage at scale channel'. However, the trade-off for such a limit is that depending on its level, it can also affect CBDC holdings in normal times. However, if the limit is set above 'normal' holdings, the effects on 'slow' disintermediation via the liquidity premium on deposits is negligible. Of course, if the limit were set below the demand of CBDC in normal times, then it would reduce the impact of CBDC on 'slow' intermediation.

Figure 7 shows how a limit affects financial stability and welfare. In our model, the optimal holding limit is in the region of €1750 for our baseline parameterization. The graph highlights that an unremunerated CBDC combined with an appropriate holding limit is superior to a world without CBDC. This is in contrast to our earlier finding of a CBDC, without a holding limit, being welfare reducing. The reason is that setting a limit that is 'high enough' in normal times, but not 'too high' in runs, exploits the benefits of 'slow' disintermediation, while limiting the damage from 'fast' disintermediation.

Initially, raising the limit above zero improves financial stability. However, once the limit becomes too large, the threat of too large movements into CBDC during financial distress becomes the dominating force again. In fact, the optimal limit is slightly *below* the demand in calm times due to the run threat.[17] More details are in table 3 and in Appendix H.

Our quantitative model is thus broadly in line with the €3000, mentioned in the European context by Bindseil (2020), Panetta (2022) and Panetta (2023a). Of course, while a significant empirical and modeling contribution, our framework is still a simplification of reality. In particular, we abstract from household heterogeneity and before any pilot or actual CBDC were to be introduced, more detailed and realistic calibration would need to be done, in a somewhat richer model.

6.2. Remuneration of CBDC

We now consider the case where the CBDC is remunerated. We allow the remuneration to depend on the nominal riskless rate on non-money assets, where the latter is pinned down by a Taylor rule, as aforementioned. We consider a simple rule, whereby the rates move in lock step, but with a wedge between the two: $R_{CB,t} = R_{I,t} - \Delta_{CB}$

To evaluate remunerated CBDC, we calibrate such that the remuneration is (close to) zero in the risky steady state, implying $\Delta_{CB} = 0.01$. The remuneration then varies with the rate cycle. During periods of credit expansion, the Taylor rule implies non-trivially positive and rising rates and, thus, CBDC receives positive remuneration. During a run, the policy rate is at the effective lower bound, implying that the rate of remuneration on CBDC is negative.

Such a remuneration scheme exploits the advantages of 'slow' disintermediation, while limiting the risk of 'fast' disintermediation, but with a very different mechanism from using holding limits. During a credit boom, CBDC is relatively attractive and it constrains to some extent the credit expansion of the banking sector, by competing with their deposit rates more effectively than an unremunerated CBDC would. Again, this increases financial stability. During a run, the remuneration turns negative, limiting the appeal of CBDC, and moderating 'fast' disintermediation.

Figure 8 illustrates some of this intuition. When comparing the dynamics during our sequence of shocks for the unremunerated and remunerated CBDC, we can see that the run probability is lower in the latter case. Furthermore, we see that the CBDC holdings

[17] Under our 'keen' parameterization, the model suggests an optimal value in the region of approximately €2750. Additional results can be found in Appendix H.

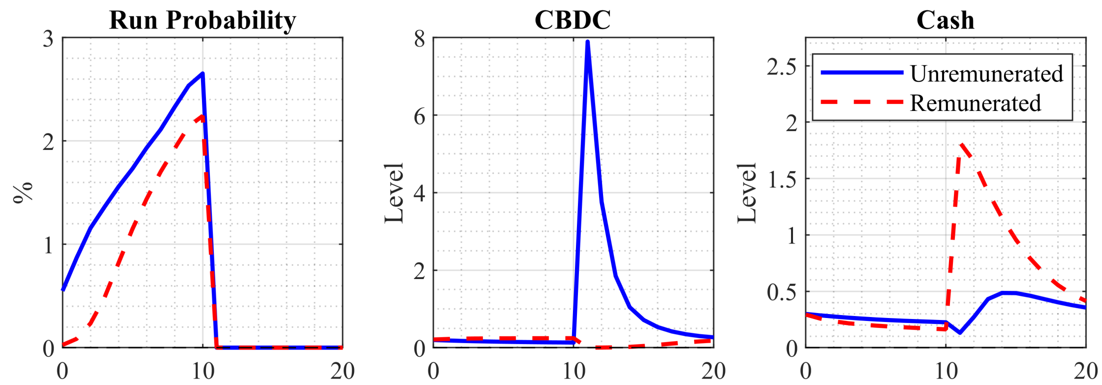

Figure 8: Comparison between an economy with unremunerated CBDC (blue solid) and remunerated CBDC (red dashed) during a credit boom gone bust. The sequence of shock is the same as in Figure 4. The scales are either annualized percent (%) or level.

are greater, prior to a run, reducing credit expansion to some extent. In the case of a run households actually reduce their remunerated CBDC holdings as it now offers a negative return. Instead, households move to cash as its return is pegged at 1. It is still the case that storage costs dampen demands for large amounts of cash, but the 'storage at scale channel' is nevertheless moderated.

As the figure already suggests, remunerated CBDC performs well in terms of welfare and financial stability. Welfare increases by 0.2% and the run probability drops to 0.92%, as shown in Table 3. Indeed, remunerated CBDC can outperform unremunerated CBDC *with optimal limits*.

Clearly there are important caveats to this result. First, we assume that the central bank wants or is permitted to offer negative remuneration, which may not be the case in some jurisdictions (a negative rate, for example, could in some jurisdictions be regarded as a tax and be consequently constrained by legislation). Second, the monetary authority must immediately offer negative CBDC remuneration during the onset of a run. If there were any lag or some mistake in setting the remuneration rate, 'fast' disintermediation could re-emerge.

Plausibly, holding limits are a simpler and more robust policy to control the effects of introducing a CBDC and, as aforementioned, seems much closer to consensus views of how a CBDC might be introduced.

7. Conclusion

We offer survey evidence that suggests there is substantial demand for CBDC, with that demand likely to lead to substitution away from other forms of money - partly out of cash, but especially out of bank deposits. This substitution is non-trivial in normal times and appears likely to be more substantial in times of banking stress. These patterns arise within a population that exhibits considerable heterogeneity. In particular, 'trust' seems to play an important role.

We incorporate the 'slow' and 'fast' disintermediation implied by our survey results in a structural model. 'Slow' disintermediation appears to have a beneficial effect on financial stability by shrinking a fragile banking system. In this sense, CBDC makes a positive contribution to financial stability. However, there is an offsetting effect if it is introduced in isolation, which is its tendency to increase run risk, or 'fast' disintermediation. This can make CBDC a destabilizing force, on net. Nevertheless, by introducing CBDC with judicious holding limits, the benefits of 'slow' disintermediation can be retained, while reducing its effect on 'fast' disintermediation, yielding welfare gains overall.

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This online appendix contains additional results connected to *CBDC and banks: Disintermediating fast and slow* (Bidder, Jackson and Rottner 2024). The views expressed in this document and all errors and omissions should be regarded as those of the authors and not necessarily those of the Bank for International Settlements, the Deutsche Bundesbank, the Eurosystem, the Bank of England, the Central Bank of Ireland, or Qatar Central Bank.

Appendix A. Survey questions

Few people are familiar with the d€ (not least because it does not yet exist!) and the concepts surrounding it. Indeed, only 27 percent of respondents asked whether they had heard of the d€ prior to the survey actually had. As such, it was necessary to give a brief introductory explanation of relevant concepts. We focused on a description that was most relevant for our purposes, abstracting from implementation details and reflecting what we perceived to be an uncontroversial stance, without being vacuous.

The rubric at the start of our set of questions was as follows, where the section in *italic* font was only (randomly) presented to a half of the respondents:[18]

> We will now turn our attention to the digital euro. The introduction of the digital euro is currently being investigated by the European Central Bank (ECB) and the national central banks of the euro area, such as the Bundesbank.
>
> The digital euro would be digital money that would be used like money on a current account. However, it would be issued and guaranteed by the ECB and the national central banks.
>
> *The digital euro would be exchangeable for euro in the form of cash at any time and also be used for payments at all times. By contrast, the availability of money on a current account with a private commercial bank depends to some extent on the stability of that commercial bank.*
>
> The digital euro would not replace cash or accounts with commercial banks, but would be an additional offering alongside these. The digital euro would enable everyday payments to be made digitally, quickly, easily, securely and free of charge throughout the euro area.

We decided to compare the digital euro (d€) to a current account to convey the ability to use it for contactless and online payments, and to distinguish it from a physical money, such as cash. Later in the survey, we make clear various assumptions about remuneration - with some respondents being asked to consider a remunerated version of CBDC so at this early point, we did not want strictly to align d€ with (zero-yielding) cash in the minds of the respondents.

We explicitly refer to issuance and backing by central banks, which is an uncontroversial assertion but then emphasize some of the implications of this - and contrasts with privately created (commercial bank) money - in the randomly assigned additional paragraph. In this paragraph we distinguish two 'availability' characteristics - that of convertibility (to cash) and usability (in transactions) - which d€ is assumed always to have, but which is not *completely* guaranteed in the case of private money issued by banks. Clearly this point can be made arbitrarily strongly, but we structured the instructions only to make the comparison qualitatively.

Appendix A.1. CBDC adoption in normal times

Our first batch of questions relate to CBDC adoption in 'normal times'. They consider a situation where d€ is absent (the *status quo*, as it were), a situation with a hypothetical unremunerated CBDC, and a situation with a remunerated CBDC.

[18]The questions were asked in German and the precise wording is listed in Appendix A.3. Further details of the survey methodology can be found here. The English form of the April 2023 (wave 40) questionnaire is here and the German version is here.

***Question 1**: Allocations without d€*

The first question posed to respondents was:

> Now imagine you had €1,000 available each month to allocate across different asset classes. In this context, please assume that the digital euro does not yet exist.
>
> How much of the €1,000 per month would you hold as cash, deposit into your current account, or invest in other financial instruments

***Question 2**: Allocations with d€*

The second question (after reminding the respondent of her previous answer) introduces the hypothetical unremunerated d€:

> Please now assume that the digital euro were to be introduced. Please also assume that you have a digital euro account that you can use to hold digital euro. You would receive no interest on this digital euro account.
>
> How much of the €1,000 per month would you now deposit into your digital euro account, hold as cash, deposit into your regular current account at your bank, or invest in other financial instruments?

***Question 3**: Allocations with Remunerated d€*

The third question related to *remunerated* CBDC. We randomly split respondents into four groups. Each was offered a hypothetical d€ paying an interest rate of 100 basis points less, 50 basis points less, equal to, or 50 basis points more than the rate on their current (bank) account. Before answering, the respondents were reminded of their answer in the unremunerated case.

> Please now assume that you would receive an interest on your digital euro account that would be - *TREATMENT* - the interest rate on your regular current account at your bank.
>
> How much of the €1,000 per month would you now deposit into your digital euro account, hold as cash, deposit into your regular current account at your bank, or invest in other financial instruments?

Reflecting the idea that these questions related to 'steady state' behavior, we asked the respondents how they would allocate a regular hypothetical amount per month among different asset classes. In addition to cash and deposits, we use a residual category for 'other financial instruments' as any finer divisions would be excessively complicated and our focus is on 'money'.[19]

For all questions, response rates were very high, with around 2-3% of missing answers on any given question.

Appendix A.2. CBDC in a stressed banking environment

Respondents were then presented with a hypothetical situation of general strains in the banking sector. We began by inviting the respondent to consider how she might *reallocate* a stock of *existing* bank deposits (€5,000, in contrast to the €1,000 flow):

***Question 4**: Allocations without d€ during bank stress*

[19] The decision to fix the amount considered at €1,000 for all respondents provides a normalization and also reflects a desire for simplicity in this dimension of what is already an intellectually demanding set of questions. Bijlsma et al. (2021) adopted a similar approach in fixing an amount for *stocks* of assets, rather than a regular *flow*, as in our case.

The next section is about money that you already have on your regular current account at your bank. Imagine that you had €5,000 on your current account.

In addition, please assume that sector according to credible news sources there are doubts about the stability of the banking. This could lead to a banking crisis that could also affect your bank. If this were to happen, you might have problems accessing your current account at short notice to withdraw money or make credit transfers.

In this situation, how much of the €5,000 would you withdraw as cash from your regular current account or invest in other financial instruments?

Question 5*: Allocations with d€ during bank stress*

Then, after reminding the respondent of her previous answer we ask the analogous question, but in the presence of a hypothetical d€:

Now please imagine that a digital euro was available as an alternative to cash and other financial assets. Please also imagine that you would receive no interest on the digital euro.

Please remember that the digital euro would be able to be exchanged for euro in the form of cash at any time and also be used for payments at all times.

where, again, the *italic* segment was only displayed to the group who (as aforementioned) were randomly chosen to receive extra information about the relative saftey of a central bank-backed money, in comparison with privately issued commercial bank money. Note also that for these questions it was made explicit that the unremunerated case was being considered.

Response rates were similar to those of the first three questions. Indeed, approximately 96% of respondents answered *all* of our questions.

Appendix A.3. German text to survey questions

Introduction

Nun geht es noch einmal um den Digitalen Euro. Die Einführung des Digitalen Euro wird aktuell von der Europäischen Zentralbank (EZB) und den nationalen Zentralbanken des Euroraums, wie z.B. der Deutschen Bundesbank, untersucht.

Der Digitale Euro wäre digitales Geld, das wie Geld auf einem Girokonto genutzt werden würde. Allerdings würde es von der EZB und den nationalen Zentralbanken herausgegeben und garantiert werden.

Der Digitale Euro könnte jederzeit in Euro in Form von Bargeld umgetauscht und auch jederzeit für Zahlungen verwendet werden. Die Verfügbarkeit des Geldes auf einem Girokonto einer privaten Geschäftsbank hingegen hängt bis zu einem gewissen Grad von der Stabilität der Geschäftsbank ab.

Der Digitale Euro würde Bargeld oder Konten bei Geschäftsbanken nicht ersetzen, sondern wäre ein zusätzliches Angebot zu diesen. Mit dem Digitalen Euro könnten alltägliche Zahlungen digital, schnell, einfach, kostenlos und sicher im ganzen Euroraum getätigt werden.

Question 1:

Nun stellen Sie sich bitte einmal vor, Sie hätten jeden Monat €1000 zur Verfügung, die Sie auf verschiedene Anlageklassen verteilen müssten. Nehmen Sie dabei bitte an, dass es noch keinen Digitalen Euro gäbe.

Wie viel der 1000€ im Monat würden Sie als Bargeld halten, auf Ihr Girokonto einzahlen oder in andere Finanzinstrumente investieren?

Question 2:

Nehmen Sie nun bitte einmal an, dass der Digitale Euro eingeführt werden würde. Gehen Sie bitte zusätzlich davon aus, Sie hätten ein Digitales Euro-Konto, auf dem Sie Digitale Euro halten können. Auf diesem Digitalen Euro-Konto würden Sie keine Zinsen erhalten.

Wie viel der €1000 im Monat würden Sie nun auf Ihr Digitales Euro-Konto einzahlen, als Bargeld halten, auf Ihr reguläres Girokonto bei Ihrer Bank einzahlen oder in andere Finanzinstrumente investieren?

Question 3:

Nehmen Sie jetzt bitte an, dass Sie auf Ihrem Digitalen Euro-Konto - **TREATMENT** - auf Ihrem regulären Girokonto bei Ihrer Bank erhalten würden.

Wie viel der €1000 im Monat würden Sie nun auf Ihr Digitales Euro-Konto einzahlen, als Bargeld halten, auf Ihr reguläres Girokonto bei Ihrer Bank einzahlen oder in andere Finanzinstrumente investieren?

Question 4:

Nun geht es um Geld, das Sie schon auf Ihrem regulären Girokonto bei Ihrer Bank haben. Stellen Sie sich vor, Sie hätten €5000 auf Ihrem Girokonto.

Gehen Sie bitte darüber hinaus davon aus, dass laut seriösen Nachrichtenquellen Zweifel an der Stabilität des Bankensektors bestünden. Daraus könnte sich eine Bankenkrise entwickeln, die auch Ihre Bank betreffen könnte. In diesem Fall könnten Sie Probleme bekommen, kurzfristig auf Ihr Girokonto zuzugreifen, um Geld abzuheben oder Überweisungen zu tätigen.

Wie viel der €5000 würden Sie in dieser Situation von Ihrem regulären Girokonto als Bargeld abheben oder in andere Finanzinstrumente(i) investieren?

Question 5:

Jetzt stellen Sie sich bitte vor, es würde einen Digitalen Euro als Alternative zu Bargeld und anderen Finanzanlagen geben. Stellen Sie sich auch vor, Sie würden für den Digitalen Euro keine Zinsen bekommen.

Denken Sie bitte daran, dass der Digitale Euro jederzeit in Euro in Form von Bargeld umgetauscht und auch jederzeit für Zahlungen verwendet werden könnte.

Wie viel der €5000 würden Sie in dieser Situation von Ihrem regulären Girokonto auf Ihr Digitales Euro-Konto überweisen, als Bargeld abheben oder in andere Finanzinstrumente investieren?

Appendix B. Additional Survey Results

Sample	ECBpref	Hightrust	Lowtrust	Aware	Highinf	Lowinf	Highinc	Lowinc	Highass	Lowass	Highdep	Lowdep	Young	Old	Transact	Unbanked	Investor	Educ	Male
All	50	28	20	91	29	20	24	24	17	30	22	20	18	45	59	5	93	36	59
Keen	63	36	10	93	25	21	27	21	18	27	20	20	20	40	59	4	93	38	59
Open	57	33	13	92	27	21	26	22	18	27	20	20	20	43	59	4	93	37	58
Sceptic	32	11	45	91	41	20	25	30	22	32	23	24	14	45	60	4	93	34	64

Table B.4: Fractions of different sample populations with particular characteristics.

Table B.5: Extensive (Probit): Full sample

	Unremunerated	Remunerated	Stress
Highinc	-0.006	0.001	-0.006
	(-0.307)	(0.079)	(-0.300)
Lowinc	-0.037*	-0.010	-0.015
	(-1.790)	(-0.515)	(-0.759)
Highass	-0.017	-0.010	-0.040**
	(-0.855)	(-0.542)	(-2.042)
Lowass	0.059**	0.038	-0.025
	(2.125)	(1.441)	(-0.897)
Highdep	-0.065**	-0.058**	-0.044*
	(-2.558)	(-2.403)	(-1.739)
Lowdep	-0.009	-0.007	-0.054***
	(-0.456)	(-0.388)	(-2.718)
Highinf	-0.024	-0.012	-0.054***
	(-1.273)	(-0.642)	(-2.914)
Lowinf	-0.009	0.003	0.013
	(-0.460)	(0.153)	(0.664)
FS	-0.016	-0.016	0.089***
	(-1.047)	(-1.104)	(6.100)
Transact	0.012	-0.006	-0.000
	(0.713)	(-0.390)	(-0.002)
Unbanked	-0.079	-0.091	-0.061
	(-1.071)	(-1.231)	(-0.788)
Investor1	-0.023	-0.014	-0.018
	(-0.764)	(-0.497)	(-0.643)
Educ	0.024	-0.001	0.040**
	(1.474)	(-0.094)	(2.526)
East89	-0.060**	-0.038	-0.067**
	(-2.109)	(-1.430)	(-2.398)
Young	-0.009	0.027	0.081***
	(-0.437)	(1.310)	(3.902)
Old	-0.078***	-0.024	-0.021
	(-4.450)	(-1.419)	(-1.262)
Male	-0.004	-0.012	-0.065***
	(-0.253)	(-0.757)	(-3.963)
Hightrust	0.095***	0.088***	0.108***
	(5.432)	(5.337)	(6.411)
Lowtrust	-0.223***	-0.195***	-0.219***
	(-10.982)	(-9.801)	(-10.284)
remun		0.000	
		(.)	
2.remun		0.158***	
		(7.839)	
3.remun		-0.246***	
		(-11.818)	
4.remun		-0.227***	
		(-10.799)	
N	4168	4168	4168

z statistics in parentheses
Note: Table displays marginal effects.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B.6: Intensive (Amounts): All sample

	Unremunerated	Remunerated	Stress
Highinc	-0.351	0.380	-0.730
	(-0.317)	(0.298)	(-0.438)
Lowinc	-0.275	0.759	-2.575
	(-0.211)	(0.550)	(-1.468)
Highass	2.142*	2.338	1.886
	(1.754)	(1.640)	(1.114)
Lowass	2.734*	1.377	1.137
	(1.681)	(0.797)	(0.468)
Highdep	1.256	2.265	3.251
	(0.808)	(1.335)	(1.407)
Lowdep	1.733	2.831**	3.251*
	(1.413)	(2.030)	(1.850)
Highinf	0.889	2.085*	-1.413
	(0.785)	(1.675)	(-0.866)
Lowinf	0.362	0.324	-0.496
	(0.314)	(0.258)	(-0.299)
FS	-1.568*	-1.145	4.945***
	(-1.720)	(-1.145)	(3.859)
Transact	-0.034	-0.522	1.471
	(-0.034)	(-0.469)	(1.005)
Unbanked	-1.959	0.241	3.271
	(-0.477)	(0.045)	(0.313)
Investor1	-0.190	0.604	2.770
	(-0.114)	(0.346)	(1.134)
Educ	-0.483	-0.940	-0.055
	(-0.511)	(-0.885)	(-0.040)
East89	2.780	1.942	-3.687
	(1.169)	(0.812)	(-1.436)
Young	-4.020***	-1.537	0.567
	(-3.564)	(-1.132)	(0.312)
Old	2.752**	1.740	3.114**
	(2.488)	(1.507)	(2.057)
Male	-0.660	-1.208	0.251
	(-0.632)	(-1.069)	(0.173)
Hightrust	0.630	1.427	3.747***
	(0.638)	(1.362)	(2.759)
Lowtrust	-1.583	0.643	2.075
	(-0.905)	(0.316)	(0.797)
remun		0.000	
		(.)	
2.remun		8.623***	
		(6.145)	
3.remun		-10.304***	
		(-7.496)	
4.remun		-9.096***	
		(-6.642)	
_cons	20.806***	26.391***	24.270***
	(9.299)	(9.966)	(7.550)
N	1403	1403	1403
R^2	0.032	0.166	0.029

z statistics in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B.7: Extensive (Probit): Full sample

	Hightrust	Lowtrust
Highinc	0.014	-0.010
	(0.764)	(-0.646)
Lowinc	-0.034*	0.019
	(-1.800)	(1.158)
Highass	-0.033*	0.041**
	(-1.836)	(2.528)
Lowass	-0.004	0.043*
	(-0.146)	(1.920)
Highdep	-0.008	-0.000
	(-0.327)	(-0.012)
Lowdep	0.010	0.028*
	(0.541)	(1.778)
Highinf	-0.133***	0.161***
	(-8.263)	(9.765)
Lowinf	0.073***	-0.014
	(3.920)	(-0.906)
Transact	0.006	0.005
	(0.398)	(0.402)
Unbanked	-0.103*	0.060
	(-1.664)	(0.975)
Investor1	-0.021	-0.017
	(-0.737)	(-0.739)
Educ	0.047***	-0.051***
	(3.068)	(-4.152)
East89	-0.090***	0.099***
	(-3.725)	(4.031)
Young	-0.038*	-0.004
	(-1.948)	(-0.222)
Old	-0.061***	0.009
	(-3.795)	(0.693)
Male	-0.003	0.081***
	(-0.206)	(6.675)
N	4168	4168

z statistics in parentheses
Note: Table displays marginal effects.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Appendix C. Contracting Problem of the Bankers

The contracting problem of the bankers draws heavily on Rottner (2023), which in turns extends the financial friction laid down in Adrian and Shin (2010) and Nuño and Thomas (2017) to incorporate endogenous runs on the financial sector. Our formulation differs as we incorporate the transaction services of deposits, which alters the maximization problem. Furthermore, the return on deposits is in nominal terms.

The banker maximizes its franchise value $V(N_t^i)$ subject to a participation constraint and incentive constraint. The participation constraint ensures that the promised interest rate payments are sufficiently high to attract deposits from the households, while the incentive constraint ensures the investment in the 'good' security. The problem of the banker j can be written down as

$$V_t^j(N_t^j) = \max_{S_t^{Bj},\bar{D}_t} (1-p_t^j)\beta E_t^N \Lambda_{t,t+1}\left[\theta V_{t+1}^j\left(N_{t+1}^j\right) + (1-\theta)(R_{t+1}^K Q_t S_t^{Bj} - \bar{D}_t^j \Pi_{t+1}^{-1})\right] \tag{C.1}$$

$$\text{s.t.}\quad (1-p_t^j)\beta E_t^N[\Lambda_{t,t+1} Q_t S_t^{Bj} \bar{b}_t^j \Pi_{t+1}^{-1}] + p_t^j \beta E_t^R[R_{t+1}^K Q_t S_t^{Bj}] \geq (Q_t S_t^{Bj} - N_t^j)\left[1 - \frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}}\right] \tag{C.2}$$

$$(1-p_t^j)E_t^N\left[\Lambda_{t,t+1}\theta V_{t+1}\left(N_{t+1}^j\right) + (1-\theta)\Big(1 - \frac{\bar{b}_t^j}{R_{t+1}^K \Pi_{t+1}}\Big) R_{t+1}^K Q_t S_t^{Bj}\right] \geq \tag{C.3}$$

$$\beta\Lambda_{t,t+1}E_t\left[\Lambda_{t,t+1}\int_{\frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}}^{\infty} \theta V_{t+1}\left(N_{t+1}^j\right) + (1-\theta)\Big(\omega - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}\Big) R_{t+1}^K Q_t S_t^{Bj} d\tilde{F}_{t+1}(\omega)\right]$$

where $\bar{D}_t^j = \bar{R}_t D_t^j$ and $\bar{b}_t^j = \left(\overline{R}_t D_t^j\right)/\left(Q_t S_t^B\right)$. We reformulate the problem as Bellman equation:

$$V_t(N_t^j) = \max_{\{\phi_t^j,\bar{b}_t^j\}} (1-p_t^j)\beta E_t^N \Lambda_{t,t+1}\left[\theta V_{t+1}\bigg(\Big(1 - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}\Big) R_{t+1}^K \phi_t^j N_t^j\bigg) + (1-\theta)(1 - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}) R_{t+1}^K \phi_t^j N_t^j\right]$$
$$+ \lambda_t^j\left[(1-p_t^j)\beta E_t^N[\Lambda_{t,t+1}\phi_t^j N_t^j \bar{b}_t^j \Pi_{t+1}^{-1}] + p_t^j\beta E_t^R[R_{t+1}^K \phi_t^j N_t^j] - (\phi_t^j N_t^j - N_t^j)\left[1 - \frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}}\right]\right]$$
$$+ \kappa_t^j\beta\bigg\{\bigg[(1-p_t^j)E_t^N\Lambda_{t,t+1}\left[\Lambda_{t,t+1}\theta V_{t+1}\left(\Big(1 - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}\Big) R_{t+1}^K \phi_t^j N_t^j\right) + (1-\theta)\Big(1 - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}\Big) R_{t+1}^K \phi_t^j N_t^j\right]$$
$$- \beta E_t\left[\Lambda_{t,t+1}\int_{\frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}}^{\infty} \theta V_{t+1}\left(\Big(1 - \frac{\bar{b}_t^j}{R_{t+1}^K}\Pi_{t+1}\Big) R_{t+1}^K \phi_t^j N_t^j\right) + (1-\theta)\Big(\omega - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}\Big) R_{t+1}^K \phi_t^j N_t^j d\tilde{F}_{t+1}(\omega)\right]\bigg]\bigg\}$$

where λ_t^j and κ_t^j are the Lagrange multipliers of the two constraints.

We start with taking the FOC for ϕ_t^j:

$$
\begin{aligned}
0 =&(1-p_t^j)E_t^N \beta \Lambda_{t,t+1} R_{t+1}^K [\theta V_{t+1}'^j + (1-\theta)](1-\overline{\omega}_{t+1}^j) \\
&+ \lambda_t^j((1-p_t^j)E_t^N \beta[\Lambda_{t,t+1} R_{t+1}^K \overline{\omega}_{t+1}^j] + p_t E_t^R \beta[\Lambda_{t,t+1} R_{t+1}^K] - [1 - \frac{\varphi_t}{\varrho_t}\mu_d \left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta m}}]) \\
&+ \kappa_t^j((1-p_t^j)\beta E_t^N \Lambda_{t,t+1} R_{t+1}^K [\theta V_{t+1}'^j + (1-\theta)](1-\overline{\omega}_{t+1}^j) \\
&- \kappa_t^j \beta E_t \Lambda_{t,t+1} \int_{\overline{\omega}_{t+1}^j}^{\infty} \left[R_{t+1}^K [\theta V_{t+1}'^j + (1-\theta)](\omega - \overline{\omega}_{t+1}^j) \right] d\tilde{F}_{t+1}(\omega) \\
&- \frac{\partial p_t^j}{\phi_t^j} E_t^N \beta \Lambda_{t,t+1} R_{t+1}^K [\theta V_{t+1}'^j + (1-\theta)](1-\overline{\omega}_{t+1}^j)\left(1+\kappa_t^j\right) \\
&- \frac{\partial p_t^j}{\phi_t^j} E_t^N \left(R_{t+1}^K \overline{\omega}_{t+1}^j - R_{t+1}^K\right)
\end{aligned}
\tag{C.4}
$$

Note that we use $\overline{\omega}_{t+1}^j = \overline{b}_t^j / (R_{t+1}^K \Pi_{t+1})$. Based on Gertler et al. (2020) and used in Rottner (2023), the last two terms are zero since at the cutoff point where the run probability is affected by the probability, $\overline{\omega}_{t+1}^j = 1$. The cutoff point is

$$
\xi_{t+1}^D(\phi_t^j) = \left\{ (\sigma_{t+1}, \iota_{t+1}) : R_{t+1}^K \frac{\phi_t^j - 1}{\phi_t^j} \overline{R}_t^D \right\}
\tag{C.5}
$$

The equation becomes then

$$
\begin{aligned}
0 =&(1-p_t^j)E_t^N \beta \Lambda_{t,t+1} R_{t+1}^K [\theta V_{t+1}'^j + (1-\theta)](1-\overline{\omega}_{t+1}^j) \\
&+ \lambda_t^j((1-p_t^j)E_t^N \beta[\Lambda_{t,t+1} R_{t+1}^K \overline{\omega}_{t+1}^j] + p_t E_t^R \beta[\Lambda_{t,t+1} R_{t+1}^K] - [1 - \frac{\varphi_t}{\varrho_t}\mu_d \left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta m}}]) \\
&+ \kappa_t^j((1-p_t^j)\beta E_t^N \Lambda_{t,t+1} R_{t+1}^K [\theta V_{t+1}'^j + (1-\theta)](1-\overline{\omega}_{t+1}^j) \\
&- \kappa_t^j \beta E_t \Lambda_{t,t+1} \int_{\overline{\omega}_{t+1}^j}^{\infty} \left[R_{t+1}^K [\theta V_{t+1}'^j + (1-\theta)](\omega - \overline{\omega}_{t+1}^j) \right] d\tilde{F}_{t+1}(\omega)
\end{aligned}
\tag{C.6}
$$

The other FOC (for $\overline{b}_t^j$) can be written as:

$$
\begin{aligned}
0 =& -\beta(1-p_t^j)E_t^N \Lambda_{t,t+1}[\theta V_{t+1}'^j + (1-\theta)] + \lambda_t^j \beta (1-p_t^j) E_t^N \Lambda_{t,t+1} \\
&- \kappa_t^j \beta (1-p_t^j) E_t^N \Lambda_{t,t+1} \left\{ [\theta V_{t+1}'^j + (1-\theta)] \right\} \\
&+ \kappa_t^j \beta (1-p_t^j) E_t \Lambda_{t,t+1} \int_{\overline{\omega}_{t+1}^j}^{\infty} \left[\theta V_{t+1}'^j + (1-\theta) \right] d\tilde{F}_{t+1}(\omega) - \theta \frac{V_{t+1}(0)}{R_{t+1}^K Q_t S_t^{Bj}} \tilde{f}_t(\overline{\omega}_{t+1}^j)
\end{aligned}
\tag{C.7}
$$

We use a guess and verify approach to continue solving the problem. In particular, we guess the following functional form for the value function:

$$
V_t = \lambda_t^j \left[1 - \frac{\varphi_t}{\varrho_t}\mu_d \left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta m}} \right] N_t^j = \lambda_t^j \Sigma_t N_t^j
\tag{C.8}
$$

where $\Sigma_t = \left[1 - \frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}}\right] = 1 - L_{D,t}$. Note that the guess involves the aggregate level of deposits, not bank j specific deposits.

We also guess that the multipliers and the bank run probability does not depend on individual characteristics, that is $\lambda_t^j = \lambda_t$, $\kappa_t^j = \kappa_t$, $p_t^j = p_t, \forall j$.

Using the guess, the incentive constraint is:

$$\begin{aligned}&\beta(1-p_t)E_t^N\left[\Lambda_{t,t+1}(\theta\lambda_{t+1}\Sigma_{t+1}+(1-\theta))(1-\overline{\omega}_{t+1})R_{t+1}^K\right] \geq \\ &\beta E_t\left[\Lambda_{t,t+1}\int_{\overline{\omega}_{t+1}^j}^{\infty}(\theta\lambda_{t+1}\Sigma_{t+1}+(1-\theta))\left(\omega-\overline{\omega}_{t+1}^j\right)R_{t+1}^K d\tilde{F}_{t+1}(\omega)\right]\end{aligned} \tag{C.9}$$

The two first-order-conditions can be written as:

$$\begin{aligned}0 =&(1-p_t)E_t^N\Lambda_{t,t+1}R_{t+1}^K[\theta\lambda_{t+1}\Sigma_{t+1}+(1-\theta)](1-\overline{\omega}_{t+1}^j)+\\ &\lambda_t((1-p_t)E_t^N[\Lambda_{t,t+1}R_{t+1}^K\overline{\omega}_{t+1}]+p_tE_t^R[\Lambda_{t,t+1}R_{t+1}^K]-\Sigma_t)\end{aligned} \tag{C.10}$$

$$\begin{aligned}0 =&-\beta(1-p_t)E_t^N\Lambda_{t,t+1}[\theta\lambda_{t+1}\Sigma_{t+1}+(1-\theta)]+\lambda_t\beta(1-p_t)E_t^N\Lambda_{t,t+1}\\ &-\kappa_t\beta\Big\{(1-p_t)E_t^N\Lambda_{t,t+1}\left[(\theta\lambda_{t+1}\Sigma_{t+1}+1-\theta)\,\tilde{F}_{t+1}(\overline{\omega}_{t+1}^j)\right]\\ &\qquad+p_tE_t^R\Lambda_{t,t+1}\left[(\theta\lambda_{t+1}+1-\theta)\left(1-\tilde{F}_{t+1}(\overline{\omega}_{t+1}^j)\right)\right]\Big\}\end{aligned} \tag{C.11}$$

At this stage, we can verify our guess about the multipliers. If we assume that the incentive constraint is binding, that is equation (C.9), then we have $\omega_t^j = \omega_t$. This implies $b_t^j = b_t$ due to $b_t^j = \overline{\omega}_{t+1}^j R_t^K$. But, then equations (C.10) and (C.11) imply that the multipliers for the constraints are equal across intermediaries, that is $\lambda_t^j = \lambda_t$ and $\kappa_t^j = \kappa_t$. The same multipliers imply the same level of leverage across intermediaries, as a binding participation constraint implies. The banks face then the same cutoff point, see equation (C.5), so that $p_t^j = p_t$. Therefore, our guess holds if both constraints are binding, that is $\lambda_t > 1$ and $\kappa_t > 0$, which we can check numerically.

Note that we assume that if there is a run on the banking sector and a banker that has invested in the bad security (off-equilibrium strategy) survives, the banker stops to operate the bank and give the remaining net worth to households, which gives $E_t^R\lambda_{t+1} = 1$.

The participation constraint and incentive constraint are as follows:

$$(1-p_t)E_t^N[\beta\Lambda_{t,t+1}\bar{R}_tD_t\Pi_{t+1}^{-1}]+p_tE_t^R[\beta\Lambda_{t,t+1}R_{t+1}^KQ_tS_t^B]+\frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}}D_t = D_t \tag{C.12}$$

$$(1-p_t)E_t^N\beta[\Lambda_{t,t+1}R_{t+1}^K(\theta\lambda_{t+1}\Sigma_{t+1}+(1-\theta))[1-e^{\frac{-\psi}{2}}-\tilde{\pi}_{t+1}]] = p_tE_t^R\beta[\Lambda_{t,t+1}R_{t+1}^K(e^{-\frac{\psi}{2}}-\overline{\omega}_{t+1}+\tilde{\pi}_{t+1})] \tag{C.13}$$

The first order conditions determine λ_t and κ_t:

$$\lambda_t = \frac{(1-p_t)E_t^N\beta\Lambda_{t,t+1}R_{t+1}^K[\theta\lambda_{t+1}\Sigma_{t+1}+(1-\theta)](1-\overline{\omega}_{t+1})}{\Sigma_t-(1-p_t)E_t^N[\beta\Lambda_{t,t+1}\overline{\omega}_{t+1}R_{t+1}^K]-p_tE_t^R[\beta\Lambda_{t,t+1}R_{t+1}^K]} \tag{C.14}$$

$$\kappa_t \tag{C.15}$$

$$= \frac{\beta(1-p_t)E_t^N\Lambda_{t,t+1}\left[\lambda_t - (\theta\lambda_{t+1}\Sigma_{t+1}+1-\theta)\right]}{(1-p_t)E_t^N\beta\Lambda_{t,t+1}\left[(\theta\lambda_{t+1}\Sigma_{t+1}+1-\theta)\,\tilde{F}_{t+1}(\overline{\omega}_{t+1})\right] + p_t E_t^R\beta\Lambda_{t,t+1}\left[(\theta\lambda_{t+1}\Sigma_{t+1}+1-\theta)\left(1-\tilde{F}_{t+1}(\overline{\omega}_{t+1})\right)\right.}$$

The last step is to verify our guess. We use the participation constraint, that we repeat here for convenience and have rewritten slightly:

$$(1-p_t)E_t^N[\beta\Lambda_{t,t+1}\overline{\omega}_{t+1}R_t^K Q_t S_t^B] + p_t E_t^R[\beta\Lambda_{t,t+1}R_{t+1}^K Q_t S_t^B] = \left(Q_t S_t^B - N_t\right)\Sigma_t \tag{C.16}$$

to determine the leverage ratio

$$\phi_t = \frac{\Sigma_t}{\Sigma_t - (1-p_t)E_t^N[\beta\Lambda_{t,t+1}\overline{\omega}_{t+1}R_t^K] - p_t E_t^R[\beta\Lambda_{t,t+1}R_{t+1}^K]} \tag{C.17}$$

We are now turning to the value function in which we insert our guess for the value function $V_t(N_t) = \lambda_t\Sigma_t N_t$:

$$\lambda_t\Sigma_t N_t = (1-p_t^j)\beta E_t^N\Lambda_{t,t+1}\left[\theta\lambda_{t+1}\Sigma_{t+1}N_{t+1} + (1-\theta)(1-\overline{\omega}_{t+1})(R_{t+1}^K Q_t S_t^B)\right] \tag{C.18}$$

$$(1-p_t^j)\beta E_t^N\Lambda_{t,t+1}\left[\theta\lambda_{t+1}\Sigma_{t+1}(1-\overline{\omega}_{t+1})(R_{t+1}^K Q_t S_t^B) + (1-\theta)(1-\overline{\omega}_{t+1})(R_{t+1}^K Q_t S_t^B)\right] \tag{C.19}$$

We can now reformulate this as an expression for λ_t

$$\lambda_t = \frac{(1-p_t^j)\phi_t\beta E_t^N R_{t+1}^K\Lambda_{t,t+1}\left[\theta\lambda_{t+1}\Sigma_{t+1} + (1-\theta)\right](1-\overline{\omega}_{t+1})}{\Sigma_t} \tag{C.20}$$

We now insert equation (C.17) to obtain:

$$\lambda_t = \frac{(1-p_t^j)\phi_t\beta E_t^N R_{t+1}^K\Lambda_{t,t+1}\left[\theta\lambda_{t+1}\Sigma_{t+1} + (1-\theta)\right](1-\overline{\omega}_{t+1})}{\Sigma_t - (1-p_t)E_t^N[\beta\Lambda_{t,t+1}\overline{\omega}_{t+1}R_{t+1}^K] - p_t E_t^R[\beta\Lambda_{t,t+1}R_{t+1}^K]} \tag{C.21}$$

This coincides with equation (C.14), which verifies our initial guess.

Appendix D. Production

There is a continuum of competitive intermediate goods producers, producing output Y_t using labor L_t and working capital K_t. Their output is sold to a final goods producing firm, while capital is purchased from capital goods producers at the market price, Q_t. Labor is supplied by households, who are paid a wage, W_t. The intermediate goods production technology for firm f is given by

$$Y_t^f = A_t(K_{t-1}^f)^\alpha (L_t^f)^{1-\alpha} \tag{D.1}$$

A_t is total factor productivity, which follows an AR(1) process. In period $t-1$ the firm purchases capital S_{t-1} and finances it with securities $S_{B,t-1}$ from the banks and the households $S_{H,t-1}$, so that $K_{t-1} = S_{H,t-1} + S_{B,t-1} + S_{G,t-1}$. The securities offer the state-contingent return R_t^K, to be discussed further below in our discussion of the bank problem.

After using the capital in period t for production, the firm sells the undepreciated capital $(1-\delta)K_t$. The intermediate output is sold at a real price $\mathcal{M}_t$, which will be equal to marginal cost φ^{mc} at the optimum. The problem can be stated as:

$$\max_{K_{t-1},L_t} \sum_{i=0}^{\infty} \beta^i \Lambda_{t,t+i} \left(\mathcal{M}_{t+i} Y_{t+i} + Q_{t+i}(1-\delta)K_{t-1+i} - R_{t+i}^K Q_{t-1+i} K_{t-1+i} - W_{t+i} L_{t+i} \right)$$

The final goods retailers buy intermediate goods and transform them into the final goods using a CES production technology:

$$Y_t = \left[\int_0^1 (Y_t^f)^{\frac{\epsilon-1}{\epsilon}} df \right]^{\frac{\epsilon}{\epsilon-1}} \tag{D.2}$$

The associated price index and intermediate goods demand that emerge from this problem are given by:

$$P_t = \left[\int_0^1 (P_t^f)^{1-\epsilon} df \right]^{\frac{1}{1-\epsilon}}, \quad \text{and} \quad Y_t^f = \left(P_t^f / P_t \right)^{-\epsilon} Y_t \tag{D.3}$$

The final retailers are subject to Rotemberg price adjustment costs. Their maximization problem is:

$$E_t \left\{ \sum_{i=0}^{T} \Lambda_{t,t+i} \left[\left(\frac{P_{t+i}^f}{P_{t+i}} - \varphi_{t+i}^{mc} \right) Y_{t+i}^f - \frac{\rho^r}{2} Y_{t+i} \left(\frac{P_{t+i}^f}{\Pi P_{t+i-1}^f} - 1 \right)^2 \right] \right\} \tag{D.4}$$

where Π is the inflation target of the monetary authority.

Competitive capital goods producers produce new end-of-period capital using final goods. They create $\Gamma(I_t/S_{t-1})S_{t-1}$ new capital S_{t-1} out of an investment I_t. Thus, they solve the following problem

$$\max_{I_t} Q_t \Gamma\left(I_t/S_{t-1}\right) S_{t-1} - I_t \tag{D.5}$$

where the functional form is $\Gamma(I_t/S_{t-1}) = a_1(I_t/S_{t-1})^{1-\eta_i}+a_2$. The resulting optimality condition defines a demand relation between the price Q_t and investment:

$$Q_t = 1/[\Gamma'\left(I_t/S_{t-1}\right)]$$

Appendix E. Global Solution Method

The model is solved with global methods to account for the endogenous runs (multiple equilibria), occasionally binding constraints (lower bounds and holding limits) and the highly nonlinear dynamics. The algorithm to find the described policy functions uses time iteration with linear interpolation based on Rottner (2023), who adapts the codes of Richter et al. (2014) for this type of model. When describing our solution approach, we heavily draw directly from the description in Rottner (2023) and adapt it to the specifics of our model.[20] While the functional space for the policy function approximation is piecewise linear, the expectations are evaluated using Gauss-Hermite quadrature, where the matrix of nodes is denoted as ε.

The model features the following 4 state variables $\mathbb{X}_t = \{S_{t-1}, N_t, \sigma_t, \iota_t\}$, where N_t is used as state variable instead of $\overline{D}_{t-1}$ for computational reasons. The parameters of the model are summarized as Θ^P. We solve for 8 policy functions $Ca(\mathbb{X}_t; \Theta^P), D(\mathbb{X}_t; \Theta^P), D_{CB}(\mathbb{X}_t; \Theta^P), Q(\mathbb{X}_t; \Theta^P)$, $C(\mathbb{X}_t; \Theta^P), \bar{b}(X), \Pi(\mathbb{X}_t; \Theta^P), \lambda(\mathbb{X}_t; \Theta^P)$, the law of motion of net worth $N'(\mathbb{X}_t, \varepsilon_{t+1}; \Theta^P)$ and the probability of a run next period $P(\mathbb{X}_t; \Theta^P)$. These objects can be used to solve all remaining variables.

To account for the multiplicity of equilibria due to possibility of a run, we use an additional piecewise approximation of the policy functions.[21] We derive separate policy functions to approximate the run and normal equilibrium. For instance, the policy functions $Ca(\mathbb{X}_t; \Theta)$ is postulated as

$$Ca(\mathbb{X}_t; \Theta^P) = \begin{cases} f^1_{Ca}(\mathbb{X}_t; \Theta^P) & \text{if no run in period } t \\ f^2_{Ca}(\tilde{\mathbb{X}}_t; \Theta^P) & \text{if run in period } t \end{cases} \tag{E.1}$$

The state variables for the run equilibrium are $\tilde{\mathbb{X}}_t = \{S_{t-1}, \sigma_t, A_t\}$ since Note that the distinct functional space for the functions $f^1_{Ca}(\mathbb{X}_t; \Theta)$ and $f^2_{Ca}(\tilde{\mathbb{X}}_t; \Theta)$ is piecewise linear.

The algorithm to find the policy functions is summarized below:

1. Define a state grid $\boldsymbol{X} \in [\underline{S}_{t-1}, \overline{S}_{t-1}] \times [\underline{N}_t, \overline{N}_t] \times [\underline{\sigma}_t, \overline{\sigma}_t]$ and integration nodes $\boldsymbol{\epsilon} \in [\underline{\epsilon^\sigma}_{t+1}, \overline{\epsilon^\sigma}_{t+1}]$ to evaluate expectations based on Gauss-Hermite quadrature
2. Guess the piecewise linear policy functions to initialize the algorithm, which includes a separate guess for each of the pieces that are related to the equilibria (e.g. $f^1_{Ca}(\mathbb{X}_t; \Theta^P)$ and $f^2_{Ca}(\tilde{\mathbb{X}}_t; \Theta^P)$)
   (a) the policy functions $Ca(\mathbb{X}_t; \Theta^P), D(\mathbb{X}_t; \Theta^P), D_{CB}(\mathbb{X}_t; \Theta^P), Q(\mathbb{X}_t; \Theta^P), C(\mathbb{X}_t; \Theta^P)$, $\bar{b}(X), \Pi(\mathbb{X}_t; \Theta^P), \lambda(\mathbb{X}_t; \Theta^P)$
   (b) a function $N'(\mathbb{X}_t, \varepsilon_{t+1}; \Theta^P)$ at each point from the nodes of next period shocks based on Gauss-Hermite quadrature
   (c) the probability $P(\mathbb{X}_t; \Theta^P)$ that a run occurs next period

[20] Note that our model is more complex to solve due to the elaborated portfolio choice underpinning our model.
[21] The ZLB introduces additional multiple equilibria. We focus only on one specific equilibrium, namely the targeted-inflation equilibrium, by choosing starting values for the policy function iteration that are taken from the targeted-inflation equilibrium.

3. Solve for all time t variables for a given state vector assuming that no run occurs to first solve for the functions related to no-run equilibrium (e.g. $f^1_{Ca}(\mathbb{X}_t;\Theta^P)$). Take from the previous iteration j the law of motion $N'(\mathbb{X}_t,\varepsilon_{t+1};\Theta^P)$ and the probability of a run $P(\mathbb{X}_t;\Theta^P)$ as given and calculate time $t+1$ variables using the guess j policy functions with X_{t+1} as state variables. The expectations are calculated using numerical integration based on Gauss-Hermite quadrature. A numerical root finder with the time t policy functions as input minimizes the error in the following five equations:

$$\mathrm{err}_1 = (\frac{\Pi_t}{\Pi_{SS}}-1)\frac{\Pi_t}{\Pi_{SS}} - \left(\frac{\epsilon}{\rho^r}\left(\varphi_t^{mc}-\frac{\epsilon-1}{\epsilon}\right)+\beta E_t\Lambda_{t,t+1}(\frac{\Pi_{t+1}}{\Pi_{SS}}-1)\frac{\Pi_{t+1}}{\Pi_{SS}}\frac{Y_{t+1}}{Y_t}\right) \tag{E.2}$$

$$\mathrm{err}_2 = 1-\beta E_t\Lambda_{t,t+1}\frac{R_{I,t}}{\Pi_{t+1}}, \tag{E.3}$$

$$\mathrm{err}_3 = (1-p_t)E_t^N\left[\beta\Lambda_{t,t+1}\bar{R}_tD_t\right]+p_tE_t^R\left[\beta\Lambda_{t,t+1}R^K_{t+1}Q_tS^B_t\right]+D_t\frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}}-D_t \tag{E.4}$$

$$\mathrm{err}_4 = (1-p_t)E_t^N\left[\Lambda_{t,t+1}R^K_{t+1}(\theta\lambda_{t+1}\Sigma_{t+1}+(1-\theta))(1-e^{\frac{-\psi}{2}}\tilde{\pi}_{t+1})\right] \tag{E.5}$$

$$-\,p_tE_t^R\left[\Lambda_{t,t+1}R^K_{t+1}(e^{-\frac{\psi}{2}}-\overline{\omega}_{t+1}+\tilde{\pi}_{t+1})\right] \tag{E.6}$$

$$\mathrm{err}_5 = \lambda_t - \frac{(1-p_t)E_t^N\Lambda_{t,t+1}R^K_{t+1}[\theta\lambda_{t+1}\Sigma_{t+1}+(1-\theta)](1-\overline{\omega}_{t+1})}{\Sigma_t-(1-p_t)E_t^N[\Lambda_{t,t+1}R^K_{t+1}\overline{\omega}_{t+1}]-p_tE_t^R[\Lambda_{t,t+1}R^K_{t+1}]} \tag{E.7}$$

$$\mathrm{err}_6 = N_t+D_t-Q_tS_{B,t} \tag{E.8}$$

$$\mathrm{err}_7 = 1+\psi_mCa_t-\left(\beta E_t\left[\Lambda_{t,t+1}\Pi^{-1}_{t+1}\right]+\frac{\varphi_t}{\varrho_t}\left(\frac{M_t}{Ca_t}\right)^{\frac{1}{\eta_m}}\right) \tag{E.9}$$

$$\mathrm{err}_8 = 1-\left(\beta E_t\left[\Lambda_{t,t+1}\Pi^{-1}_{t+1}\right]R_{CB,t}+\frac{\varphi_t}{\varrho_t}\mu_{cb}\left(\frac{M_t}{D_{CB,t}}\right)^{\frac{1}{\eta_m}}\right) \tag{E.10}$$

Note that in the no CBDC economy, $D_{CB}(\mathbb{X}_t;\Theta^P)$ is set to zero and only the first seven error terms are minimized. Regarding the occasionally binding constraints, we directly use a max operator for the effective lower bound. When focusing on holding limits for CBDC, a slightly smoother approach is used for computational reasons. Instead of directly imposing a limit, a punishment term enters the first order condition if $D_{CB} > \bar{D}_{CB}$. The function to minimize is then written as

$$\mathrm{err}_8 = 1+\tilde{\psi}_{\bar{D}_{CB}}\max[D_{CB,t}-\bar{D}_{CB},0]-\left(\beta E_t\left[\Lambda_{t,t+1}\Pi^{-1}_{t+1}\right]R_{CB,t}+\frac{\varphi_t}{\varrho_t}\mu_{cb}\left(\frac{M_t}{D_{CB,t}}\right)^{\frac{1}{\eta_m}}\right) \tag{E.11}$$

where the value $\tilde{\psi}_{\bar{D}_{CB}}$ is set to a sufficient high value so that $D_{CB,t}\leq\bar{D}_{CB}$ holds approximately for the entire grid

4. Take the iteration j policy functions , $N'(\mathbb{X}_t,\varepsilon_{t+1};\Theta^P)$ and $P(\mathbb{X}_t;\Theta^P)$ as given and solve the whole system of time t and $(t+1)$ variables. Calculate then N_{t+1} using the "law of

motion" for net worth

$$N_{t+1} = \max\left[R^K_{t+1}Q_tS_{B,t} - \overline{R}_tD_t, 0\right] + (1-\theta)\zeta S_t. \tag{E.12}$$

A run occurs at a specific point if

$$R^K_{t+1}Q_tS_{B,t} - \overline{R}_tD_t \leq 0. \tag{E.13}$$

In such a future state, the weight of a run is 1. In the other state, the weight of a run 0.[22] This can be now used to evaluate the probability of a run next period based on Gauss-Hermite quadrature so that p_t is known.

5. Repeat steps 3 and 4 for the run equilibrium so that the piece of the policy functions related to the run equilibrium is solved for (e.g. $f^2_{Ca}(\mathbb{X}_t;\Theta^P)$)
6. Update the policy policy functions: $Ca(\mathbb{X}_t;\Theta^P), D(\mathbb{X}_t;\Theta^P), D_{CB}(\mathbb{X}_t;\Theta^P), Q(\mathbb{X}_t;\Theta^P), C$ $(\mathbb{X}_t;\Theta^P), \bar{b}(X)$, $\Pi(\mathbb{X}_t;\Theta^P), \lambda(\mathbb{X}_t;\Theta^P)$ slowly. For instance for cash-policy function, this could be written as:

$$Ca_{j+1}(\mathbb{X}_t;\Theta^P) = \alpha^{U1}Ca_j(\mathbb{X}_t;\Theta^P) + (1-\alpha^{U1})Ca_{sol}(\mathbb{X}_t;\Theta^P), \tag{E.14}$$

where the subscript *sol* denotes the solution for this iteration and α^{U1} determines the weight of the previous iteration. Furthermore, $N'(\mathbb{X}_t,\varepsilon_{t+1};\Theta^P)$ and $P(\mathbb{X}_t;\Theta^P)$ are updated using the results from step 4:

$$N'_{j+1}(\mathbb{X}_t,\varepsilon_{t+1};\Theta^P) = \alpha^{U2}N'_j(\mathbb{X}_t,\varepsilon_{t+1};\Theta^P) + (1-\alpha^{U2})N'_{sol}(\mathbb{X}_t,\varepsilon_{t+1};\Theta^P), \tag{E.15}$$

$$P_{j+1}(\mathbb{X}_t;\Theta^P) = \alpha^{U3}P_j(\mathbb{X}_t;\Theta^P) + (1-\alpha^{U3})P_{sol}(\mathbb{X}_t;\Theta^P). \tag{E.16}$$

7. Repeat steps 3 - 6 until the errors of all functions, which are the policy functions $Ca(\mathbb{X}_t;\Theta^P)$, $D(\mathbb{X}_t;\Theta^P), D_{CB}(\mathbb{X}_t;\Theta^P), Q(\mathbb{X}_t;\Theta^P), C(\mathbb{X}_t;\Theta^P), \bar{b}(X), \Pi(\mathbb{X}_t;\Theta^P), \lambda(\mathbb{X}_t;\Theta^P)$ together with the law of motion of net worth $N'(\mathbb{X}_t,\varepsilon_{t+1};\Theta^P)$ and the probability of a run $P(\mathbb{X}_t;\Theta^P)$, at each point of the discretized state are sufficiently small.

[22] This procedure would imply a zero and one indicator, which is very unsmooth. For this reason, the following functional forms based on exponential function are used: $\frac{\exp(\zeta_1(1-D_{t+1}))}{1+\exp(\zeta_1*(1-D_{t+1}))}$ where $D_{t+1} = \frac{R^k_{t+1}}{R^D_t}\frac{\phi}{\phi-1}$ at each calculated N_{t+1}. ζ_1 is set to 2500. This large value of ζ ensures sufficient steepness so that the approximation is close to an indicator function of 0 and 1.

Appendix F. Endogenous runs and the role of CBDC: Event Analysis

Figure F.9 shows an event analysis based on a simulation of 100000 periods. It shows the average response (with the 68% and 90% confidence interval) across all observed runs, displaying 10 periods prior and after the run. The analysis highlights that the main dynamics as shown in our sequence of shocks has very similar dynamics as the typical run in the model.

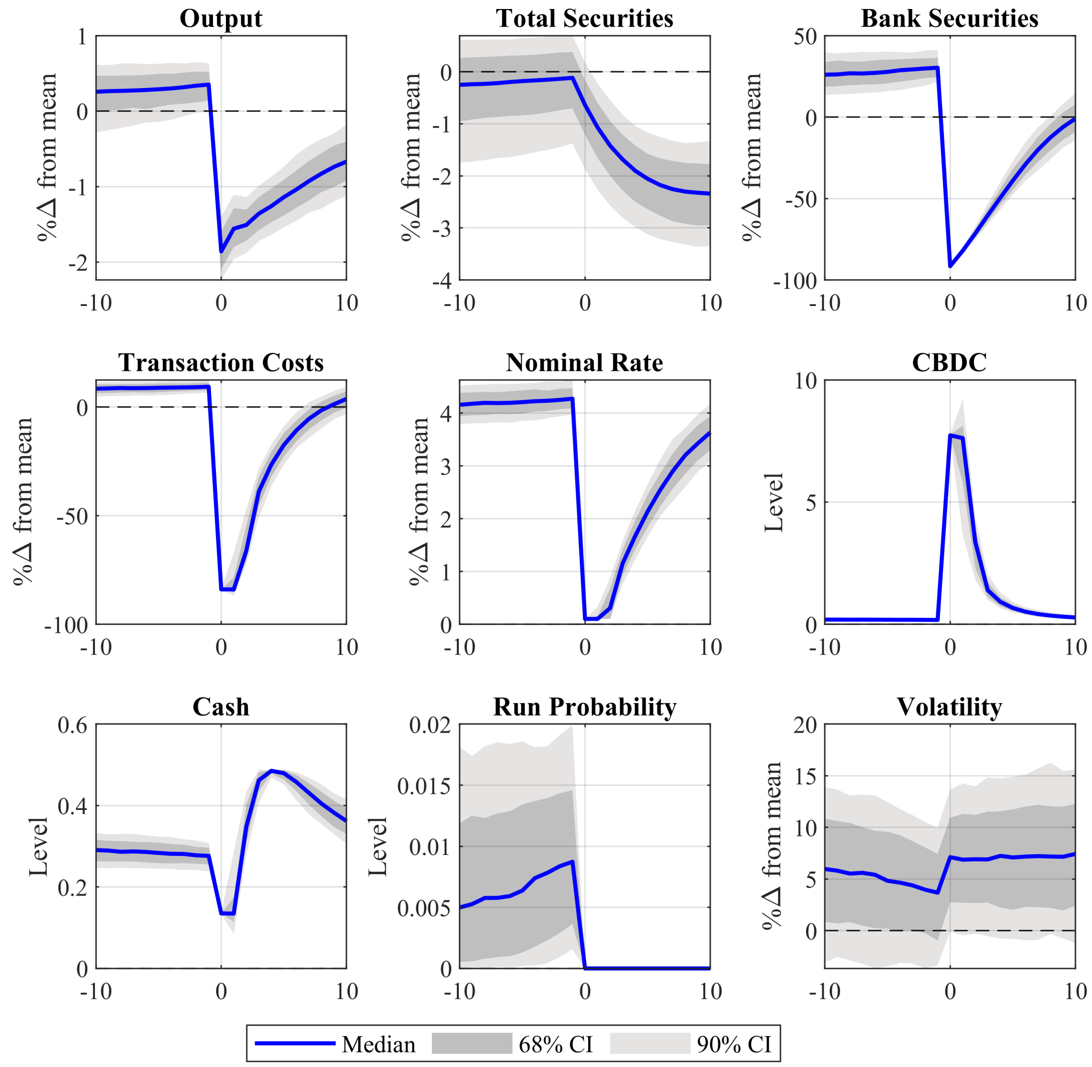

Figure F.9: Event analysis based on a simulation of 100000 periods. It shows the average response across (with the 68% and 90% confidence interval) across all observed runs using an event window (10 periods before and the run). The scales are either percentage deviations from the average ($\%\Delta frommean$), percent (%) or level.

Appendix G. CBDC Demand and Equilibrium Impact

Figure G.10 shows the impact of variations in the weight of CBDC μ_{cb} in the money aggregator on the equilibrium.

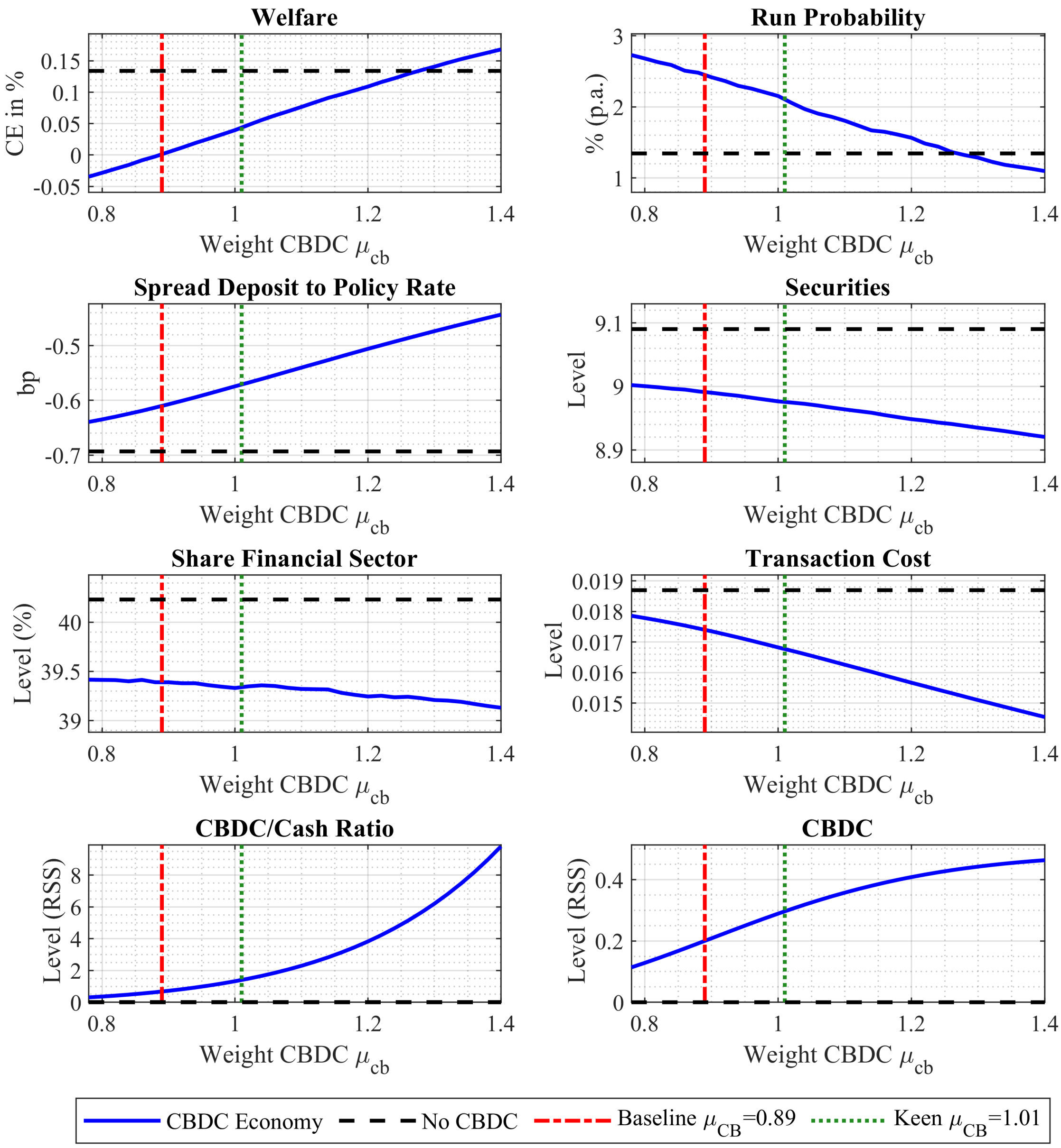

Figure G.10: Impact of variations in the weight of CBDC μ_{cb} in the money aggregator on the equilibrium (blue line). Baseline scenario (red dash-solid), keen scenario (green footed) and no CBDC scenario (black dashed) are highlighted. Most variables display their mean. CBDC-cash-ratio and CBDC values are shown for the risky steady state values. The scales are either consumption equivalent in percent (CE in %), annualized percent (% p.a.), level or basis points for annualized spread (bp).

Appendix H. Policy Design

Appendix H.1. Optimal Limit for Baseline Scenario

Figure H.11 shows the impact of a holding limit $\bar{D}_{CB}$ for the baseline scenario. Relative to the main text, the impact on more variables is shown. The optimal limit is located around 0.17.

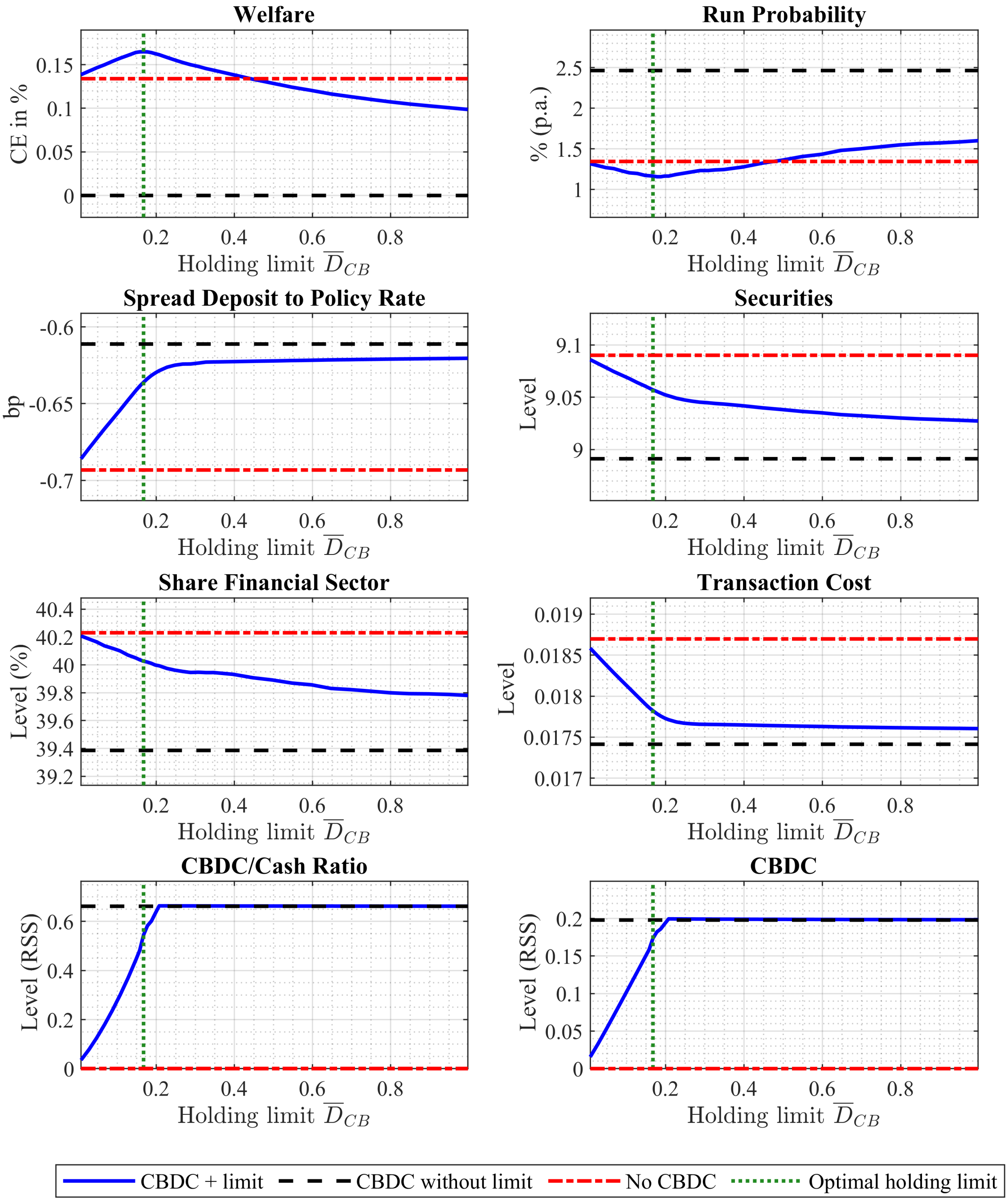

Figure H.11: Impact of holding limits for CBDC $\overline{D}_{CB}$ on the equilibrium (blue line) for the base scenario $\mu_{cb} = 0.89$. The horizontal lines show CBDC without limit (black dashed) and the economy without CBDC for comparison. Most variables display their mean. CBDC-cash-ratio and CBDC values are shown for the risky steady state value The scales are either consumption equivalent in percent ($CEin\%$), annualized percent (% p.a.), level or basis points for annualized spread (bp).

Appendix H.2. Optimal Limit for Keen Scenario

Figure H.12 shows the impact of a holding limit $\bar{D}_{CB}$ for the keen scenario. The optimal limit is located around 0.27.

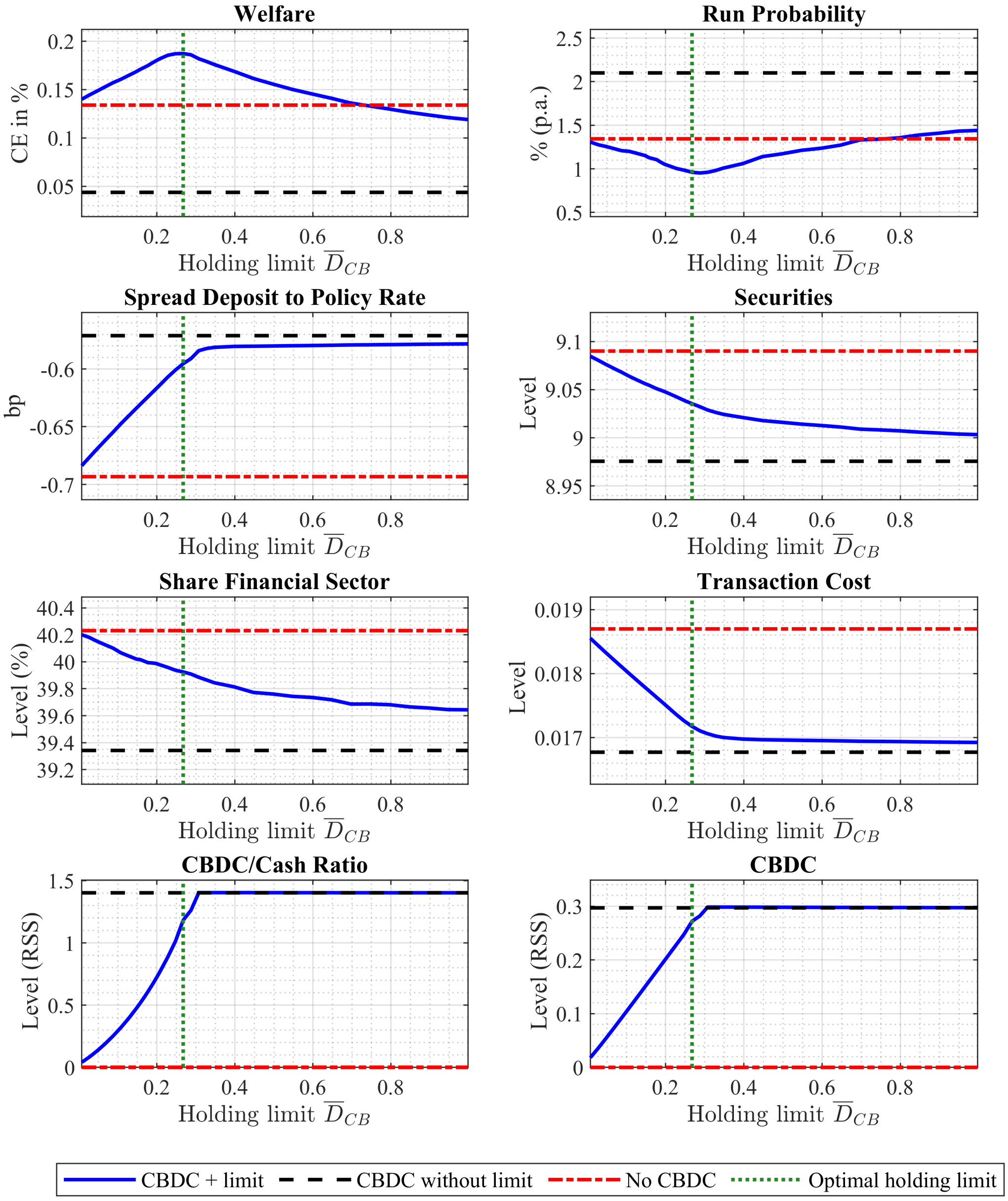

Figure H.12: Impact of holding limits for CBDC $\overline{D}_{CB}$ on the equilibrium (blue line) for the keen scenario $\mu_{cb} = 1.01$. The horizontal lines show CBDC without limit (black dashed) and the economy without CBDC for comparison. Most variables display their mean. CBDC-cash-ratio and CBDC values are shown for the risky steady state value The scales are either consumption equivalent in percent ($CEin\%$), annualized percent (% p.a.), level or basis points for annualized spread (bp).

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