CBDC and banks: Disintermediating fast and slow

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Abstract

We examine the impact of central bank digital currency (CBDC) on banks and the broader economy - drawing on novel survey evidence and using a structural macroeconomic model with endogenous bank runs. A substantial share of German respondents would include CBDCs in their portfolio in normal times - replacing, in part, commercial bank deposits. This is hypothetical evidence for 'slow' disintermediation of the banking system. During periods of banking distress, households' willingness to shift to CBDC is even larger, implying a risk of 'fast' disintermediation. Our structural model captures both phenomena and allows for policy prescriptions. We calibrate to the Euro area and then introduce CBDC, exploiting our survey to parameterize its demand. We find two contrasting effects of CBDC on financial stability. 'Slow' disintermediation shrinks a run-prone banking system with positive welfare effects. But the ability of CBDC to offer safety at scale makes bank-runs more likely. For reasonable calibrations, this second 'fast disintermediation' effect dominates and the introduction of CBDC decreases financial stability and welfare. However, complementing CBDC with a holding limit or pegging remuneration to policy rates can reverse these results such that CBDC is welfare improving. Such policies retain the gains of increased stability arising from 'slow' disintermediation while limiting the downsides of 'fast' disintermediation.

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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...
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> Fabio Panetta, April 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.
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> Board of Governors, January 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 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. While fast and slow disintermediation are individually important, they 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 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.

Clearly, in the absence of a functioning CBDC it is difficult to establish targets for economic modeling and risk assessments. As such, surveys about hypothetical usage, particularly in such an influential country as Germany, are especially useful. Based on answers from approximately 6000 respondents to the Deutsche Bundesbank's Survey on Consumer Expectations we gain insight into how people might allocate funds across different asset classes in various contingencies, where the assets considered include cash, commercial bank deposits, and digital Euro deposits. Specifically, we ask how they would allocate

[1] See the database of CBDC projects in Auer et al. (2023).

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. We also find a strong tendency to withdraw to digital Euro in times of banking stress. If we define 'openness' by projecting positive holdings of unremunerated CBDC or paying up to 25 basis points more than their bank account, or withdrawing positive amounts to a digital Euro in the times of banking stress, then around 86% of respondents appear 'open' to CBDC.

These results have important implications for banks. Among the 'keen' group, there is an average decline of approximately 14% (4 percentage points) in cash shares and of 27% (14 percentage points) in bank deposit shares on the introduction of an unremunerated CBDC in normal times. 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 even stronger among those whom we randomly treated with additional information about the relative safety of central-bank backed money, in comparison with private money that is only backed by commercial banks. The dominant asset withdrawn to is cash, though the presence of the digital Euro again is influential. Just over a fifth of deposits (on average) are left in bank accounts in the absence of a CBDC but this falls by around 5 percentage points in its presence. In fact, if a digital Euro is available, almost a fifth of deposits are projected to be withdrawn to it, conditional on our 'distressed banks' scenario.

Our theoretical contribution is to build a medium scale DSGE framework that is capable of addressing these same issues, and which can be used to analyse a variety of emerging policy questions around CBDC. An important technical feature of the model is that it is solved globally, which is vital, first, for permitting multiple equilibria (Diamond-Dybvig type runs) and, second, to handle the substantial nonlinearities that arise from the very distinct regimes that the model exhibits, where edge-cases (such as a complete loss of deposits by incumbent banks) abound. Indeed, in extensions to the model, we address an extremely hotly debated practical policy question – the level at which to set any 'holding limits' for CBDC – which implies inherent nonlinearity. The model can also handle a zero lower bound to policy rates.

We can therefore analyze both fast and slow disintermediation in a unified framework. Deposits, cash and CBDC co-exist as substitutable types of money available to households, along with securities issued by non-financial firms. In normal times, incumbent banks intermediate between households and firms. The risk of a run arises endogenously from the interaction of these banks' leverage decisions and households' willingness – and, in some cases, refusal – to provide deposit funding.

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 (following Adrian and Shin (2010) and Nuño and Thomas (2017)). As in Rottner (2023), 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 also Gertler et al. (2020)).

At sufficiently high leverage, multiple equilibria emerge in which beliefs of a run can be self-confirming. During a run, households stop rolling over their deposits and banks must sell their assets, leading to a drop in the value of their holdings, inducing losses that justify the run in the first place. Given that banks are the most efficient financiers in the economy (more so than households or the government), there is a destruction of resources associated with this shift in ownership of the assets.

CBDC is a completely safe alternative asset with payment capabilities and the scope to be held in large quantities. As such, it competes with bank deposits in normal times, reducing the liquidity premium obtainable by banks on their deposits. This slow disintermediation implies banks are smaller and would imply reduced run-risk except that CBDC also provides a haven in runs, which, unlike cash, can be held in arbitrarily large amounts. We find that fast combined with slow disintermediation implies that banks are somewhat disintermediated in steady state, and the risk of runs is, all else equal, also increased. The model generates this result under realistic assumptions, including holding costs of cash that increase rapidly with the amount, which contrasts with CBDC technology that allows storage at scale without increasing holding costs for households. Unlimited CBDC is welfare-reducing under our baseline calibration, reflecting the dominance of fast disintermediation on financial stability, rather than slow.

Many countries have discussed holding limits as a feature of at least the initial launch of any retail CBDC. Importantly, we show that – with correctly calibrated holding limits – the introduction of CBDC is *welfare improving*. In normal times, these holding limits allow households to almost fully satiate their demand. Their key contribution is in times of vulnerability. Specifically, holding limits mitigate CBDC's aforementioned tendency to spark runs as it can no longer be held in arbitrarily large amounts. What remains, however, is the stabilizing effect on the financial system due to (some) slow disintermediation:

making banks smaller and less run-prone in the first place. Ironically, (limited) slow disintermediation overturns welfare losses of fast disintermediation – despite oft-raised concerns about both effects.

An active debate exists over the level at which holding limits should be set. Values around €3000 have been mooted in relation to a digital Euro, while substantially larger amounts (between £10,000 and £20,000) have been mentioned in the debate over a digital pound sterling. While our model makes a substantial contribution to realism in modeling CBDC, we only with temerity offer a prescription for the optimal amount, as the framework still omits several real-world dimensions. It also requires a more thorough treatment of the welfare implications of central bank balance sheet and the modeling of the costs and benefits of a central bank's choice of assets in its portfolio. Nevertheless, based on our preferred calibration and assessed prospective demand for CBDC, the model suggests an optimal limit level ranging between €1500 and €2500 for CBDC holdings.

While our focus is on holding limits and unremunerated CBDC, reflecting the direction current debates seem to be taking, a second CBDC design feature often discussed (though less often in recent times) is whether or not to remunerate CBDC holdings. Our framework allows us to consider this question. We model the rate on CBDC as tracking the standard policy rate (which follows a Taylor rule), less 25 basis points. Even in the absence of holding limits, CBDC can then be welfare improving, reflecting the fact that it endogenously becomes much less attractive in runs, reflecting the rate of remuneration declining as the economy weakens, combined with the Taylor rule, drags down the the interest rate on nominally riskless, non-money assets.

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). Embedding CBDC in generic macroeconomic models has been achieved in Burlon et al. (Forthcoming), Barrdear and Kumhof (2022), Abad et al. (2024) 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, which is key to many of the most pressing debates over CBDC.

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. (2023), Keister and Sanches (2022), Jackson and Pennacchi (2021) and Chiu et al. (2023) focus on what we would term 'slow disintermediation'. They discuss how bank funding costs and, ultimately, lending might be influenced in steady state, acknowledging the substitutability of CBDC as a payments technology for cash and bank deposits (see also Chiu and Monnet (2023) for a framework featuring *other* types of money - namely stablecoins and tokenized deposits).[2] Chiu et al. (2023) has philosophical parallels with ours in that it has a flavor of 'second best' reasons why CBDCs could be welfare enhancing (Lipsey and Lancaster (1956)). However, their mechanism (related to market power among banks) is very different from ours, where undesirable financial fragility can be offset through a combination of CBDC and holding limits.

Both slow and fast disintermediation is discussed in, for example, 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 (see also BoE (2020) and Bindseil (2020) for early discussions of this topic). Befitting the importance of the subject, there are many recent contributions, including Kumhof and Noone (2021), Williamson (2022), Keister and Monnet (2022), Kim and Kwon (2022), Ahnert et al. (2023), Fernández-Villaverde et al. (2021) and Muñoz and Soons (2023). 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. Indeed, the model is calibrated to key macroeconomic moments and further disciplined by information taken from questions on CBDC included in a survey of German households. As the launch – or at least pilots – of CBDCs becomes imminent, this transition from stylized models (often k-period, or static), to more policy-relevant frameworks is vital.

In analyzing the role of CBDC holding limits we contribute to a topic that is currently hotly debated (see Panetta (2023b), ECB (2023), Angeloni (2023) and House of Commons (2023)). Nevertheless, other than contemporaneous work in Meller and Soons (2023) there is little academic research, as yet, on this topic. Meller and Soons (2023) provide a thorough accounting- or 'constraint'-based analysis of bank balance sheet evolution and bring important regulatory data to bear on the question, but do not offer a macroeconomic model (see Muñoz and Soons (2023), however, for related work).

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

[2]As a substitute for cash, Rogoff (2017) and Bordo and Levin (2019) argue CBDC may allow central banks to discontinue high-denomination banknotes which facilitate tax evasion and illicit trading.

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 (through being backed by a central bank and being legal tender) of CBDC, relative to private money, issued by banks.

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 that implement incentive compatible investment behavior by the banks. The leverage constraints tighten (loosen) as risk increases (decreases) in the economy. This generates a 'volatility paradox' (see Brunnermeier and Sannikov (2014)) where financial fragility that ultimately cause volatility 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. The survey comprises three strands:

- **Expectations of aggregate objects:** Inflation, house prices and rents, interest rates on saving accounts and loans
- **Household behavior and characteristics:** Demographics, current and past expenditures, balance sheet and income
- **Topical policy issues:** Questions added temporarily to investigate particular topics of interest

As part of the 'topical policy issues' segment, we included 5 questions in CBDC, for wave 40 (April 2023), issued to approximately 5700 respondents. On the basis of these questions we are able to attain qualitative, but also quantitative insights which allow us to discipline our model. Given the (obvious) absence of a production roll-out of a digital Euro (d€) these results are useful for preliminary insights into adoption in a major European economy.

2.1. CBDC 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:[3]

> 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.

[3]The questions were asked in German and the precise wording is listed in Appendix A. 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.

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.

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*, as it were), 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.
>
> 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?

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 50 basis points less, 25 basis points less, equal to, or 25 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'.[4]

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

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 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.

[4]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.

2.2. Survey results

In this section, we outline the results of the survey, distinguishing between normal times and periods of banking stress. We will use elements of the survey to discipline our model. However, the extent to which we can do so is obviously constrained by also having to match aggregate moments that may not be consistent with the raw survey evidence and by the stylized nature of our model (though less stylized than other existing models). Nevertheless, we outline some of the most striking empirical findings as they are of independent interest - particularly those that highlight how different characteristics shape the adoption of CBDC. The results may also provide empirical targets for future work.

2.2.1. CBDC adoption in 'normal times'

To begin, we report what fraction of the sample indicated they would hold a positive amount of d€ in the unremunerated case, and in the (randomly assigned) remunerated cases. That is, we first analyze the 'extensive margin' of adoption.

Rate	1	R_d-25bp	R_d	R_d+25bp
Percent	45.9	34.4	57.3	72.6

Table 1: Percent of respondents who project positive holdings of dEUR when unremunerated (Q2) and when remunerated to different degrees (Q3), relative to checking account R_d

Table 1 illustrates what fraction of the sample indicated they would hold a positive amount of dEUR in the unremunerated case, and in the (randomly assigned) remunerated cases. Just under half of the respondents project a desire for d€ in the unremunerated case (45.9 percent). However, if d€ offers the same remuneration as the respondents' current accounts, then that number rises to 57.3%. The adoption rate declines (rises) by about 23 (15) percentage points in moving from remuneration at the current account rate, to remuneration at 25 basis points lower (higher).

It is, of course, important to acknowledge that the general rates environment (and in particular rates available on alternative assets) should matter for CBDC adoption – most obviously if it is unremunerated, as appears likely for many CBDC projects. Given that we ran the survey in April 2023, when the typical rate on current accounts was somewhat below 25 basis points, we might expect the projected adoption rate to lie between the rates in the cases of remunerated rates at 25 basis points below (34.4 percent) and equal to the current account rate (57.3 percent), and that is indeed what we find.

In the left panel of figure 1 we see the average portfolio allocation across the survey sample with all respondents considered. Looking at the portfolios, the projected interest in CBDC is around 10%. The d€ to cash ratio is around 56%, indicating substantial interest, though of course cash clearly remains a

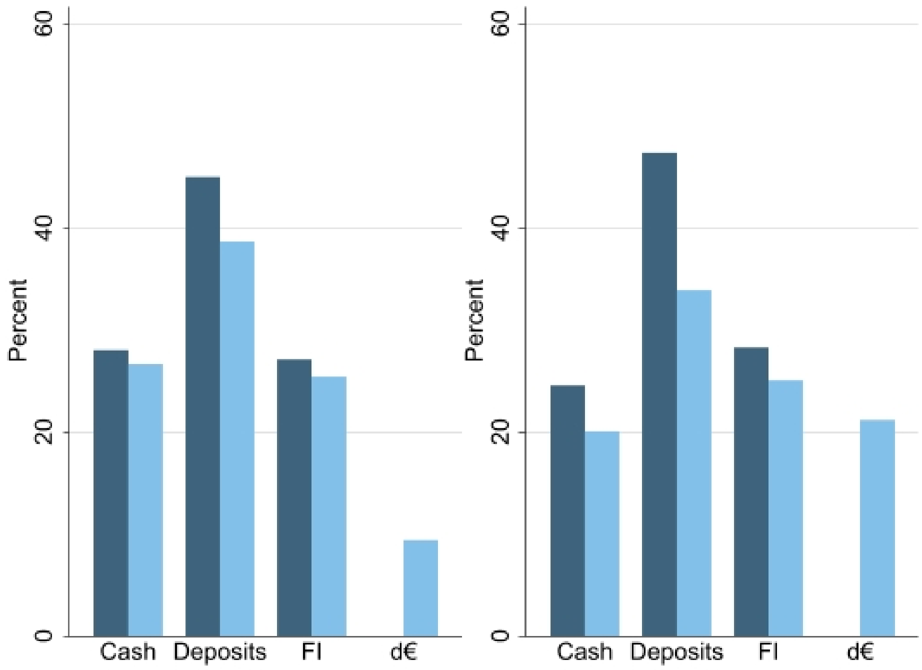

Figure 1: Portfolio decisions of households in normal times. Dark blue (left bar) displays shares without d€, while light blue (right bar) displays shares with d€. The columns correspond to cash, deposits, other financial instruments, d€ (from left to right). The left panel shows the average for the 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.

desirable asset. We observe movements out of all other asset classes 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. Looking at the portfolios of these respondents is arguably an interesting experiment. *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. It is also, of course, more suited to calibrating parameters that influence decisions on the intensive margin.

Among the 'keen' group, unremunerated d€ is projected to be approximately 21% of the portfolio. 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 all of the other asset classes. Table 2 shows these changes for various sub-samples of respondents. Cash and deposits decline, on average, by around 14% and 27% respectively.[5] The share of other financial instruments declines by about 10%.

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, grouping cash and deposits, there

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

is a substantial shift out of extant forms of money - both physical and digital. Therefore, the results indicate some 'slow' disintermediation resulting from the introduction of the d€. Again, we note that, all else equal, a higher rate environment than the one prevailing when the survey was run might moderate the shift out of deposits and other investments into an *unremunerated* CBDC. In fact, our results discussed below suggest strongly that respondents are indeed aware of real and nominal rates of return and, on average, respond to marginal incentives in these dimensions.

Importantly, 87 percent of respondents fall into a category we refer to as 'open' to CBDC. These are respondents who are keen *or* project positive zero holdings when d€ pays equal to or 25 basis points more than their current account, *or* withdraw positive amounts to d€ in a time of (hypothetical) banking stress. As aforementioned, the 'keen' group accounts for approximately 46 percent. We can also identify 'reluctant' respondents, as defined by not projecting positive holdings even when offered 25 basis points above their current account rate. These represent only 7 percent of the sample. It is notable that in the right context, a very large majority of Germans appear open to d€.

These results help to reduce our uncertainty over how the public may respond to a CBDC. As noted in Angeloni (2023) these unknowns are profoundly important for initial design decisions of the d€:

> If the substitution is (mainly) with cash, it would be a replacement of one form of central bank money for another, with minimal or zero effect on the financial system. This is unlikely to happen though: all information we have suggests that euro area citizens wish to retain their cash holdings; actually, they are concerned that the [d€] may be a covert way to abolish cash. More likely is the case that the substitution will be mainly with bank deposits. The real unknown is the extent of such substitution.

While we find less substitution out of cash than out of bank deposits, the degree to which our respondents project a move from cash to CBDC is non-trivial.

2.2.2. CBDC adoption and heterogeneity

The survey is extremely rich in the data it gathers from households. Given the observed heterogeneity among respondents, it is of course important to control for comovements in explanatory variables in capturing their association with d€ adoption and portfolio decisions. The variables we use can loosely be categorized as 'economic', 'demographic', 'activity', and 'trust'-based.

Categories. Within the 'economic' category we have measures of income, assets and liabilities (aggregate and composition), inflation expectations, available savings rates and so forth. The quantitative responses on income and wealth are typically discretized with answers given in terms of ranges of values and with some (though typically not very binding) top-coding. We create dummies for groups with the highest or lowest values reported and incorporate these into our estimation specifications. An additional variable we create is a ratio of deposits relative to assets, given our focus on money usage.[6] As one might expect, this ratio is typically very high for the poorest respondents (in terms of lowest aggregate value of assets) and low for the more asset-rich. We also include a dummy for whether or not the respondent was randomly treated with extra information about the relative benefits of d€ in times of banking problems, as aforementioned.

In terms of 'demographics', we know the respondent's age, gender, educational background, and whether they were based in East Germany in 1989. We characterize 'young' respondents as those under 40. We construct a variable indicating if the respondent was an *adult* in East Germany in 1989 - attempting to capture exposure to an authoritarian government. We also possess information on what region the respondent *currently* lives in, and the approximate size of settlement/city where they are based.

In terms of 'activities', the survey helpfully distinguishes whether the respondent is primarily responsible, in their household, for certain tasks. Two of these roles are undertaking 'day to day transactions' (a 'transactor' respondent), and managing saving/investment decisions (an 'investor' respondent). We can also proxy whether a respondent is 'unbanked' (low wealth, with no bank deposits).

Finally, we consider another split of the respondent pool - into those who report especially high and especially low trust in the ECB, where trust is *ostensibly* in relation to the ECB's ability to deliver price stability. In addition, we flag whether they are aware of recent policy rate changes.

Results. We focus on describing the factors that affect (hypothetical) holdings of CBDC on both the extensive (based on probit) and intensive margins of d€ adoption. While we present the regressions in detail in tables B.7 (extensive) and B.8 in the appendix, we here highlight some key results.

We observe the key importance of 'trust' for the adoption of the d€. Figure 2 shows the portfolio changes for the two groups.[7] Being of high trust (in the ECB) raises the probability of adoption by about 7 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.[8] 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 East German regime is associated with a reduction

[6] For this we roughly construct a ratio by first imputing the midpoint value to the different intervals associated with each class of asset considered (deposits, real estate, securities, equity in unlisted businesses, other) and then taking the ratio for deposits relative to the aggregate.

[7] Note that we include respondents within both these groups who project zero holdings of dEUR so we are blending intensive and extensive margin patterns.

[8] The high (low) trust respondents account for approximately 28 (20) percent of the survey sample.

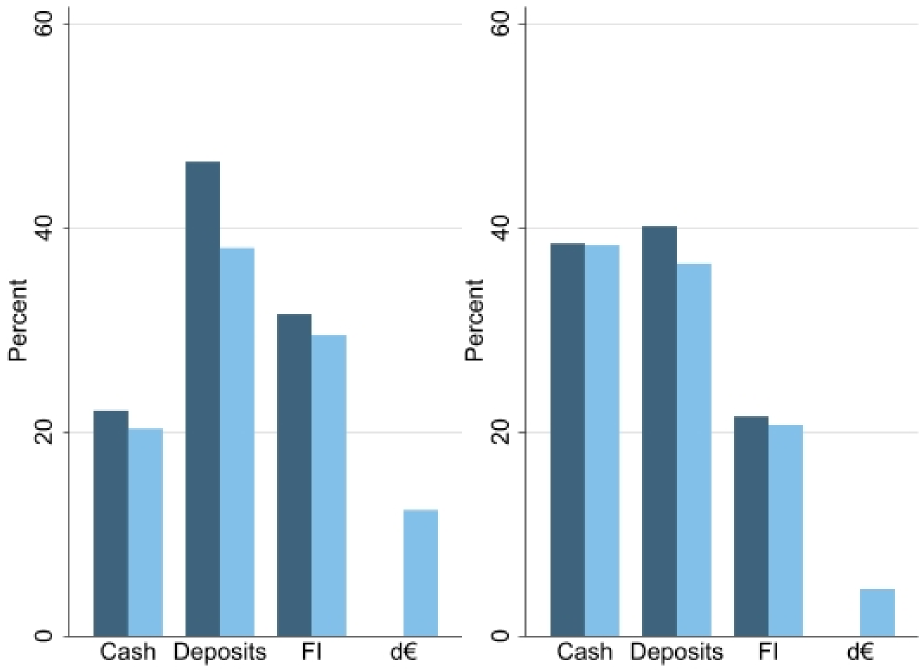

Figure 2: Portfolio decisions of high trust (left) and low trust (right) households. Dark blue (left bar) displays shares without d€, while light blue (right bar) displays shares with d€. The columns correspond to cash, deposits, other financial instruments, d€ (from left to right). Each chart refers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

of approximately 4 percentage points, which chimes with many of the privacy concerns raised by those sceptical about a CBDC (see also Patel and Ortlieb (2020), Bijlsma et al. (2021) and Choi et al. (2023) on similar points).

We note that trust in the ECB remains extremely influential in the regression, even when controlling for inflation expectations (or *high* expectations of inflation).[9] Furthermore, as shown in table 2, it is striking how large a share of assets the low trust group wish to hold as cash - given that their low trust is *supposedly* in relation to the ECB's ability to maintain price stability. One would expect that a fear of inflation might deter people from holding (nominally) zero yielding assets such as cash. It is plausible, therefore, that the trust measure is capturing a broader sense of unease.

There are other intuitive and statistically significant coefficient estimates in the regression. There is a suggestion that older respondents are substantially less likely to project positive d€ holdings, while younger ones are more likely to adapt the d€. These results chime well with expectations. In addition, those who are concerned with day to day purchases ('transactors') seem somewhat more positive, perhaps reflecting an understanding that a d€ could be a superior form of money for transactions in retaining the backing of a central bank - like cash - but with scope for online and contactless payments. On the extensive margin we also observe a hint of better-off respondents – those likely to have access to higher yielding alternative assets – being somewhat less likely, all else equal, to adopt an unremunerated d€.

One somewhat surprising coefficient estimate on the extensive margin is the negative coefficient on

[9]High inflation is associated with a 3 percentage point lower probability of adoption.

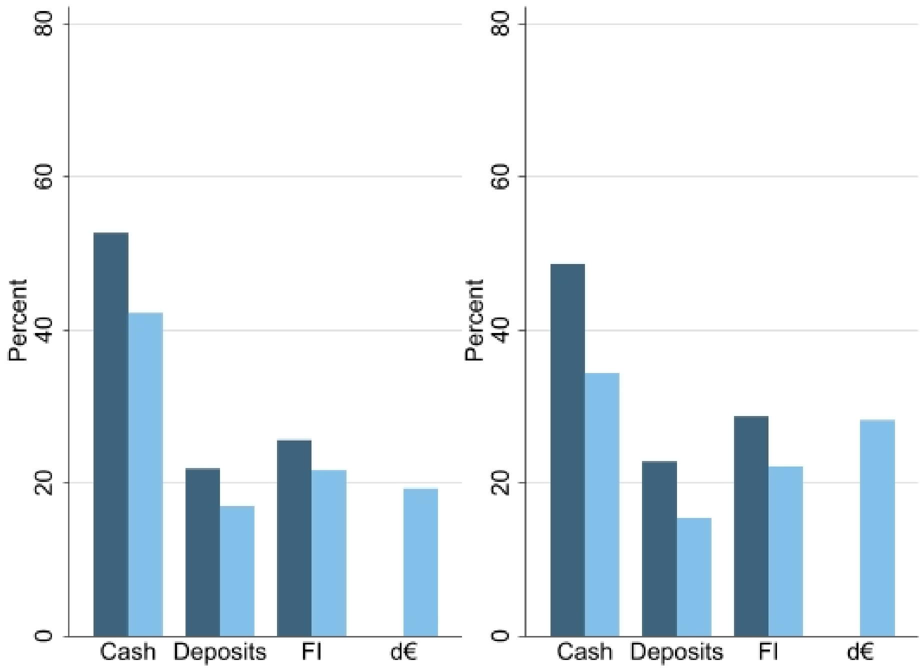

Figure 3: Average withdrawal shares of households during banking stress. Dark blue (left bar) displays shares without d€, while light blue (right bar) displays with d€. The columns are cash, deposits, other financial instruments, d€ (from left to right). The left panel shows the average for the entire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

the 'unbanked' (those low net worth individuals who report not having any deposits). The introduction of CBDC is frequently depicted as improving financial inclusion (see the CBDC survey run annually by the BIS, for example). As such, one might have expected a positive coefficient. The interpretation of this result is difficult. Plausibly, it may reflect insufficient explanation of the benefits of CBDC for such individuals. Three quarters of the unbanked had not heard of CBDC before completing this survey and it may well be the case - especially since our rubric compared CBDC to having a digital bank account - that they assumed that CBDC is 'not for them'. This interpretation supports the targeting of CBDC education towards the unbanked - and those who are suspicious of the ECB.

2.2.3. CBDC and withdrawals in times of banking stress

We turn now to how respondents predicted they might behave in times of banking stress, in terms of how much and into what asset classes they might withdraw funds from commercial bank accounts. Figure 3 illustrates average withdrawal patterns for all respondents, and for the 'keen' group.

On average, there appears to be somewhat greater openness to d€ in times of stress, with a 56 percent rate of positive withdrawals to d€, compared with the 'normal times' d€ adoption rate of adoption of 46 percent.[10] 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

[10]Note that this is a comparison between allocating incoming funds (Q2 and Q3) versus reallocating existing funds already in a bank account (Q5).

	d€				Cash				Deposits			
	Q1 vs Q2		Q4 vs 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	-12.36	-4.86	-23.35
Keen	21.1	20	28.12	20	-4.02	-13.51	-14.19	-19.14	-13.56	-26.75	-7.33	-28.22
Open	10.87	5	22.35	16	-1.63	-5.41	-11.96	-16.38	-7.22	-14.85	-5.73	-26.42
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 2: 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.

bank money. 61 percent stated they would withdraw to d€ among those who were treated with extra information, in contrast to 51 percent among those who did not receive the extra information. When educated about possible advantages of a CBDC, households on average seem likely to respond, implying some delicate communications and strategic decisions by policymakers. As noted in Monnet and Niepelt (2023) and Angeloni (2023), some believe policymakers face a challenge in making the d€ successful, but not 'too' successful - that is, not causing 'excessive' disruption of the existing financial system. We also note that there are parallels in our results with those of Sandri et al. (2023) who find that treating households with news about Silicon Valley Bank has a clear effect on households' perceptions of banks' stability.

Among those who projected zero d€ in normal times, approximately a third stated they would withdraw to it in times of banking stress. 38 (26.3) percent stated they would withdraw to d€ among those who were treated (not treated) with extra information. Even among the approximately 1000 respondents who projected zero d€ holdings in normal times *despite being offered the same or 25 basis points above their current account rate*, just over a fifth project to withdraw to an *unremunerated* d€ in times of stress. The swing was approximately 27 (19) percent among those treated (not treated) with extra information. Again, on average, respondents seem to grasp the relative attractiveness of d€ in times of banking stress and the effects of informing the public on this matter can be quite powerful. Since we (randomly) issued guidance on the superiority safety on CBDC in arguably the gentlest way possible, it is perhaps striking how strong an effect there is.

Looking instead among those who projected positive holdings of unremunerated d€ in steady state (45.9 percent of respondents), around 84 percent project that they would withdraw to d€ in run times. Conditional on receiving (not receiving) the extra information about d€'s availability and convertibility, the rate is 88 (80) percent approximately. The effect of information among those already open to d€ (as based on question 2) is relatively small, compared with the effect in the case of those not projected to

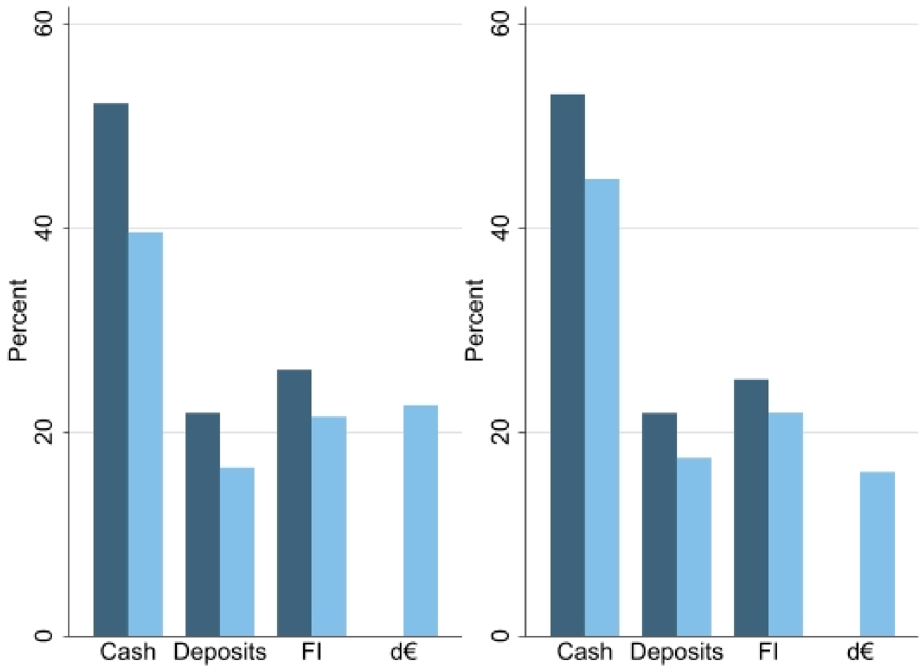

Figure 4: Average withdrawal shares during banking stress. Dark blue (left bar) displays shares without d€, while light blue (right bar) displays with d€. The columns are cash, deposits, other financial instruments, d€ (from left to right). The first column is in the presence of randomly receiving extra information on the safety of the d€ and the second is in its absence.

hold d€ in steady state. It is possible that those willing to hold d€ in steady state are doing so precisely because they *already* understand the benefits of d€ in a period of banking stress, but that is difficult to prove conclusively.[11]

Figure 3 illustrates the average fraction of bank deposits that respondents project they would withdraw in times of banking stress (comparing Q4 and Q5). 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 (figure 3) 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 2. In fact, as the figure shows, once d€ is available, almost a fifth of deposits are withdrawn to it. This is close to the amount withdrawn to other financial assets, and more than is left in the deposit account. The presence of d€ reduces the withdrawals to cash by around 10 percentage points (or 14 percent) and to other financial assets by around 4 percentage points (or 13 percent).

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

[11] Indeed, a non-trivial fraction of those who projected positive d€ in normal times, project zero holdings in times of stress. It is perhaps surprising that there are some who would hold d€ in steady state but *not* withdraw to it in fraught times, though there may be some explanations. Plausibly, in a stressed context, people may wish to cleave to familiar assets such as cash, or perhaps those they regard as a *hedge* for uncertainty or risks that emerge in banking crises. It could also be the case that they may envisage high returns to certain assets firesold at that time.

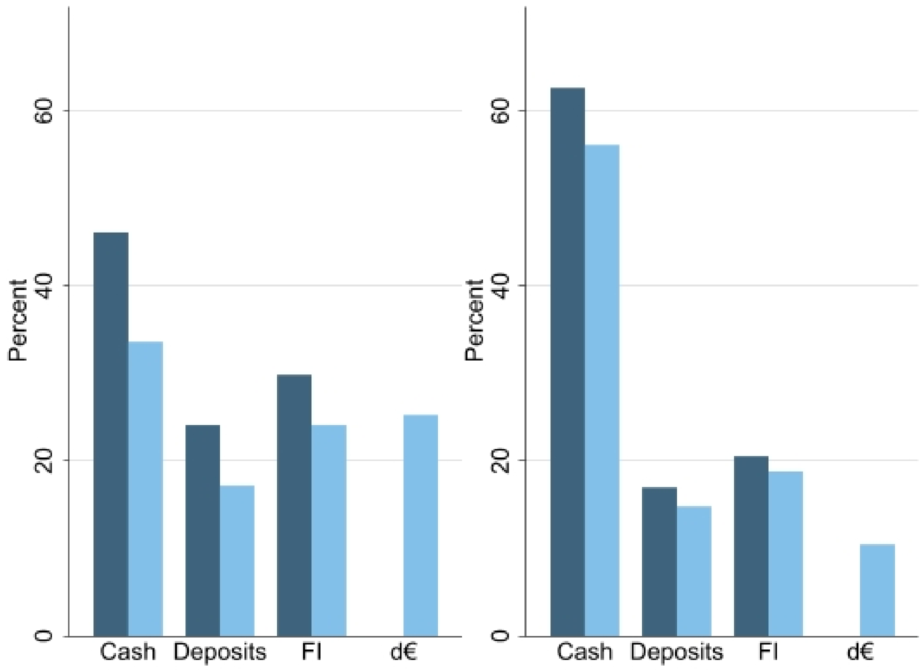

Figure 5: Average withdrawal shares during banking stress of households exhibiting high and low trust in the ECB. Dark blue (left bar) displays shares without d€, while light blue (right bar) displays with d€. The columns are cash, deposits, other financial instruments, d€ (from left to right). The left (right) panel shows the average for high (low) trust respondents.

- an important factor incorporated in our model discussed below. As discussed above, receiving extra information on the relative 'availability' benefits of d€ in comparison to bank deposits has a strong effect, as shown in figure 4, where we examine the impact among all respondents and also among the 'keen'.

Trust continues to play an enormous role on the extensive margin and on the intensive margin, high trust in the ECB has a strong positive association with withdrawals to d€, as shown in figure 5. Even low trust (of the ECB) respondents withdraw in nontrivial amounts to d€, though at a much lower rate than high trust respondents. Striking in this diagram is the overwhelming tendency of low trust individuals to withdraw to cash.

2.3. Using the survey to discipline the model

We primarily rely on historical aggregate data to map our model to the data. Such a strategy is impossible to calibrate the adoption of CBDC as, clearly, the d€ does not exist in reality. Therefore, we exploit our survey to parameterize the demand for CBDC, a key metric to evaluate the economic, financial stability and welfare impact of CBDC. It is a significant contribution of our paper that, unlike other work modeling CBDC completely in the absence of data, we can at least draw on our survey results.

Throughout our analysis we repeatedly make use of the survey results for the whole sample, but also conditioning on the responses of the 'keen' respondents - that is, those that projected positive unremunerated d€ holdings. Furthermore, setting aside our 'marginal' information on d€ the survey also provides us with 'joint' information on multiple asset classes. In both model and survey we allow for cash, deposits, CBDC and non-monetary financial assets.

3. Model

Our model features two key components. First, it allows for a concept of financial fragility by incorporating a banking sector that is vulnerable to endogenous bank runs, based on Rottner (2023) (see also Gertler et al. (2020)). Second, we allow for the coexistence of CBDC with other forms of money - bank deposits and cash. In addition to featuring in household portfolio decisions as 'assets', money has a particular value to households by reducing transactions costs, as in Schmitt-Grohé and Uribe (2010). We compare the behavior of the economy in the absence and presence of CBDC, and under various design decisions on the manner in which CBDC is implemented.

3.1. Household

A representative household comprises workers and bankers with perfect within-household insurance. Household consumption is denoted by C_t. Workers supply labor, L_t, and earn a wage, W_t. 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.

3.1.1. Portfolio decision

The household has access to four types of assets: 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. Strictly, 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 (or think of them as being contained in the Ξ_t term in the budget constraint, (5), below.

While bank deposits *promise* in t a nominal face return of $\bar{R}_t$ in $t+1$, the household receives only a fraction x_{t+1} of the promised return in the case of a run. We refer to x_{t+1} as the 'recovery ratio', which will be determined endogenously.[12] Thus the realized return on deposits is given by:

$$R_t = \begin{cases} \bar{R}_{t-1} & \text{if } \iota_t = 0 \text{ (no run in period } t\text{)} \\ x_t \bar{R}_{t-1} & \text{if } \iota_t = 1 \text{ (run in period } t\text{)} \end{cases} \tag{1}$$

[12] Although we abstract from deposit insurance in the model, the main takeaways are robust as long as deposit insurance is imperfect (see also Ikeda and Matsumoto (2021)). An imperfect deposit insurance implies that the deposits are only partly protected so that it is individually optimally to run to avoid losses. Therefore, we would just need to assume that bank failure is associated with some deadweight losses, as in many papers done.

For simplicity, we will let the variable ι_t be a dummy that indicates whether a run is occurring in t or not.

As in Gertler et al. (2020), we distinguish between beginning-of-period capital K_t that is 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 Γ which will be explained shortly. It is convenient to refer to claims on capital-in-progress as securities S_t which evolve according to:

$$S_t = (1-\delta)S_{t-1} + \Gamma\left(I_t/S_{t-1}\right)S_{t-1}. \tag{2}$$

The households' end of period securities, $S_{H,t}$, give them a direct ownership in the non-financial firms. The household earns a stochastic rental rate Z_t and can trade the securities with other households and banks at price, Q_t.[13]

Funding from households and banks are perfect substitutes from the perspective of the firm. That is, the same amount of capital can be funded with equivalent amounts of household or bank financing. As discussed below, the inefficiency of direct financing from households is captured through an implicit utility cost, rather than through any explicit inferiority in technology. Total end-of-period securities holdings S_t are:

$$S_t = S_{H,t} + S_{B,t} + S_{G,t} \tag{3}$$

where $S_{B,t}$ and $S_{G,t}$ are the securities held by banks and government, respectively.

Households may also hold balances in cash, Ca_t. When holding cash, the households face storage costs $\psi(Ca_t)$. We assume that the unit costs of storing cash are positive and are increasing in the total amount, that is $\psi(Ca_t) > 0, \psi'(Ca_t) > 0$ and $\psi''(Ca_t) > 0$ if $Ca_t > 0$. This feature makes it expensive to hold very large amounts of cash, as in reality. Modeling such costs are particularly important to assess extreme events such as a run. Following the functional form of Burlon et al. (Forthcoming), the costs are given by

$$\psi(Ca_t) = \frac{\psi_m}{2} Ca_t^2 \tag{4}$$

where we assume $\psi_m > 0$.

The households may also hold CBDC, $D_{CB,t}$, if the central bank issues it. CBDC either pays a

[13] In terms of notation, the various returns and interest rates considered in this paper are expressed as nominal variables, whereas other variables, unless explicitly stated, are real.

(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. We will discuss below how $R_{CB,t}$ is determined, when we specify the activities of the central bank and fiscal authority.

3.1.2. Budget constraint

Given the above, the budget constraint of the household is given by

$$\begin{aligned}(1+s_t)C_t + Q_t S_{H,t} + Ca_t + D_t + D_{CB,t} + \psi(Ca_t) + T_t &= W_t L_t + (Z_t + (1-\delta)Q_t)S_{H,t-1} + \Xi_t \\ &+ \Pi_t^{-1}\left(Ca_{t-1} + D_{t-1}R_t + D_{CB,t-1}R_{CB,t-1}\right)\end{aligned} \quad (5)$$

where T_t references 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. s_t denotes transaction costs incurred in purchasing units of consumption, as in Schmitt-Grohé and Uribe (2010). The transaction costs depend on velocity, $v_t \equiv C_t/M_t$.[14]

$$s_t = s_1\left(v_t + s_2 v_t^{-1} - 2\sqrt{s_2}\right) \quad (6)$$

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

$$M_t = \left[Ca_t^{\frac{\eta_m-1}{\eta_m}} + \mu_d D_t^{\frac{\eta_m-1}{\eta_m}} + \mu_{cb} D_{CB,t}^{\frac{\eta_m-1}{\eta_m}}\right]^{\frac{\eta_m}{\eta_m-1}} \quad (7)$$

where we assume $\eta_m > 1$. This implies that the different types of money are substitutable, where the degree of substitutability increases with η_m.

3.1.3. Utility and optimality

The *lifetime* utility function of the household maximizes is

$$U_t = E_t\left[\sum_{\tau=t}^{\infty} \beta^{\tau-t}\left\{u(C_\tau, L_\tau, S_{H,\tau}, S_{CB,\tau}) - \Gamma(S_{H,\tau}, S_\tau)\right\}\right] \quad (8)$$

where the *period* utility function is

$$u(C,L) \equiv \frac{C^{1-\sigma^h}}{1-\sigma^h} - \chi\frac{L^{1+\varphi}}{1+\varphi}. \quad (9)$$

[14] 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, as in 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

$$\Gamma(S_{H,t}, S_{CB,t}, S_t) \equiv \frac{\Theta_\Gamma}{2}\left(\frac{S_{H,t} + \Theta_{CB} S_{CB,t}}{S_t} - \gamma^F\right)^2 S_t \tag{10}$$

where $\Theta > 0$ and $\gamma^F > 0$. An increase in households' share in capital holdings increases the utility costs, but only if $S_{H,t}/S_t > \gamma^F$. 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.[15] Ultimately, the aim of this reduced form approach, as in Gertler et al. (2020), is to incorporate 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.

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. As a consequence, we have a parsimonious assumption to vary the efficiency of the central bank's portfolio, in terms of its impact on welfare. Again this is a reduced form for a much richer theory of the costs and benefits of central bank balance sheet structure and size - a theory that is long overdue but which is beyond the scope of this paper.

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

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

[15]Furthermore, any large non-bank intermediaries who invest on behalf of households would themselves encounter the same issue of being less specialist monitors than banks, and would implicitly pass on additional costs through their fees, making the price of investing in firms securities higher or, perhaps more intuitively, the effective return lower.

The second term in the denominator of $\tilde{R}_{K,t+1}$ captures the aforementioned wedge in pricing that emerges 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.

The optimality conditions for the money assets are given as

$$1 + \psi_m Ca_t = \beta E_t \left[\Lambda_{t,t+1}\Pi_{t+1}^{-1}\right] + \frac{\varphi_t}{\varrho_t}\left(\frac{M_t}{Ca_t}\right)^{\frac{1}{\eta_m}} \tag{12}$$

$$1 = \beta E_t \left[\Lambda_{t,t+1}\Pi_{t+1}^{-1}\right] R_{CB,t} + \frac{\varphi_t}{\varrho_t}\mu_{cb}\left(\frac{M_t}{D_{CB,t}}\right)^{\frac{1}{\eta_m}} \tag{13}$$

$$1 = \beta E_t \left[\Lambda_{t,t+1}\Pi_{t+1}^{-1} R_{t+1}\right] + \frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}} \tag{14}$$

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 $\varphi_t/\varrho_t = s'(v_t)v_t^2 = s_1(v_t^2 - s_2)$, we see that 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 one period risk-pricing kernel is given by $\Lambda_{t,t+1} \equiv \varrho_{t+1}/\varrho_t$. 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 first-order conditions with respect to bank deposits and CBDC can be combined to yield

$$sp_{D,t} \equiv \frac{\bar{R}_t}{R_{CB,t}} = \zeta_{1,t} \times \zeta_{2,t} \tag{15}$$

where sp_t is the spread of the face return on deposits, over the remuneration of CBDC, with

$$\zeta_{1,t} \equiv \frac{1 - L_{D,t}}{1 - L_{CB,t}} \tag{16}$$

and

$$\zeta_{2,t} = \frac{E_t[\Lambda_{t,t+1}\Pi_{t+1}^{-1}]}{p_t E_t^R[\Lambda_{t,t+1}\Pi_{t+1}^{-1}x_{t+1}] + (1-p_t)E_t^{NR}[\Lambda_{t,t+1}\Pi_{t+1}^{-1}]} \tag{17}$$

The interpretation of $\zeta_{1,t}$ is that the relative 'prices' of the gross returns (which would have been 1/1 in the absence of a monetary friction) are adjusted by the marginal (period) utilities obtained from holding the two type of money.

$\zeta_{2,t}$ is a ratio of 'bond' prices but with the partial default (the size of which is determined by x_{t+1}) contingency of the bank deposit reflected in the denominator. This weighs on the demand for deposits, such that $\zeta_{2,t} > 1$. Note that p_t is the probability of a run in $t+1$ given information in t, while E_t^R and E_t^{NR} are expectations operators conditional on a run occurring or not occurring in $t+1$, respectively. Thus, in the absence of a particular desire for bank deposits on the margin, arising from the transaction benefits it brings relative to those from CBDC (captured in $\zeta_{1,t}$), bank deposits would necessarily offer a positive spread over CBDC.

It should be noted at this point, that households will only provide deposits to banks if they believe that it will offer them a sufficient, risk- and cost-adjusted, return. As such, a participation condition of the following form must be satisfied if banks are to be funded in the current period:

$$p_t \beta E_t^R[\Lambda_{t,t+1} R_{K,t+1}] Q_t S_{B,t} + (1-p_t)\beta E_t^{NR}[\Lambda_{t,t+1}\Pi_{t+1}^{-1}]\bar{R}_t D_t \geq D_t\,(1 - L_{D,t}) \tag{18}$$

In the case of a run next period, the household receives the gross return on securities, which is all the bank has to offer, given that it cannot honor $\bar{R}_t$ in full. As such, the left-hand side represents the appropriately discounted value of their deposits, which should be at least as great as their outlay, adjusted for the utility benefits arising from the transaction services of deposits.

Similarly, we can compare the spread between the return of cash over CBDC

$$sp_{Ca,t} \equiv \frac{1}{R_{CB,t}} = \frac{1 + \psi_m Ca_t - L_{Ca,t}}{1 - L_{CB,t}} \tag{19}$$

Relative prices are adjusted by the marginal (period) of utilities from holding the two types of money. Cash incurs a storage cost while CBDC does not. Thus, if CBDC is unremunerated ($R_{CB,t} = 1$) and households are indifferent between the money types ($\mu_{CB} = 1$), households will hold relatively more CBDC than cash.[16] Importantly, this relative preference is state-dependent: increasing storage costs tempers the demand for cash in a run. By contrast, the scalability of CBDC facilitates fast disintermediation.[17] We later discuss specific design choices for CBDC that affect the fast disintermediation capacity of CBDC.

3.2. 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

[16]Cash and CBDC are not perfectly substitutable provided η_m is finite so some cash-demand will remain.
[17]These concerns (though he may not have necessarily shared them) are well articulated by Fabio Panetta in the quote at the start of our paper.

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 is given by

$$Y_t^j = A_t (K_{t-1}^j)^{\alpha} (L_t^j)^{1-\alpha} \tag{20}$$

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:

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

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

$$P_t = \left[\int_0^1 (P_t^j)^{1-\epsilon} df \right]^{\frac{1}{1-\epsilon}}, \quad \text{and} \quad Y_t^j = \left(P_t^j / P_t \right)^{-\epsilon} Y_t \tag{22}$$

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

$$E_t \left\{ \sum_{i=0}^{T} \Lambda_{t,t+i} \left[\left(\frac{P_{t+i}^j}{P_{t+i}} - \varphi_{t+i}^{mc} \right) Y_{t+i}^j - \frac{\rho^r}{2} Y_{t+i} \left(\frac{P_{t+i}^j}{\Pi P_{t+i-1}^j} - 1 \right)^2 \right] \right\} \tag{23}$$

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

$$\max_{I_t} Q_t \Gamma\left(I_t / S_{t-1}\right) S_{t-1} - I_t \tag{24}$$

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:

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

3.3. Banks

The banks' leverage decision 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. Specifically, they 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 choose a strategy that is too risky from the depositors' point of view. 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. Aside from this incentive constraint, the banks also incorporate the possibility of runs in their decision problem, as a run eradicates their net worth, which they are dynamically attempting to maximize.[18]

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 from intermediate goods producers:

$$Q_t S_t^{Bj} = N_t^j + D_t^j. \tag{25}$$

Leverage is defined as $\phi_t^j = Q_t S_t^{B,j}/N_t^j$.

The bank chooses its capital structure and portfolio to maximize its franchise value, V_t. In the face of financial frictions, this 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. As aforementioned, the probability of a run next period is denoted p_t, which is endogenous and state-dependent. We defer the derivation of p_t to the next section. The value of

[18]Recall also, as shown in equation 18, banks funding depends also on run risk through households' portfolio decisions.

the bank is then

$$V_t^j(N_t^j) = (1-p_t)E_t^{NR}\left[\Lambda_{t,t+1}\left(\theta V_{t+1}^j(N_{t+1}^j) + (1-\theta)(R_{t+1}^K Q_t S_t^{Bj} - R_{t+1}D_t^j)\right)\right], \tag{26}$$

Since a run wipes out the entire net worth, the continuation value in a run contingency is zero. The bank maximizes the franchise value subject to incentive and participation constraints resulting from the risk-shifting incentives, as now described.[19]

Risk-Shifting Incentives and Volatility. We follow Christiano et al. (2014) in our design of the risk shifting problem. After purchasing the 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 i.i.d 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 $\log \omega_t = 0$.[20] In the 'bad' case we have that

$$\log \omega_t \overset{iid}{\sim} N\left(\frac{-\sigma_t^2 - \psi}{2}, \sigma_t\right), \tag{27}$$

where $\psi < 1$. σ_t, which affects the idiosyncratic volatility, is an exogenous driver of risk, to be specified below. The substandard 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.[21] 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.

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

$$\sigma_t = (1-\rho^\sigma)\sigma + \rho^\sigma \sigma_{t-1} + \sigma^\sigma \epsilon_t^\sigma, \tag{28}$$

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

[20] 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.

[21] $1 > e^{-\frac{\psi}{2}}$ and $0 < [e^{\sigma^2} - 1]e^{-\psi}$, where we recall $\psi < 1$

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

$$R_t^K \equiv \frac{(1-\delta)Q_t + Z_t}{Q_{t-1}} \tag{29}$$

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:

$$\overline{\omega}_t^j = \frac{\bar{R}_{t-1}^D D_{t-1}^j}{R_t^K Q_{t-1} S_{t-1}^{Bj}}. \tag{30}$$

The threshold applies regardless of which conversion type the bank chooses, though the substandard security is more likely to fall below this value due to the lower mean and higher variance. Note also that the threshold is state-dependent, reflecting the 'systemic' risk arising from the randomness of R_t^K.

Were it not for limited liability, the financial entities would choose to invest in the good security as it has a higher mean and lower variance. 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 thus:

$$\tilde{\pi}_t^j = \int^{\overline{\omega}_{t+1}^j} (\overline{\omega}_{t+1}^j - \tilde{\omega}) dF_t(\tilde{\omega}) > 0. \tag{31}$$

In contrast, there is no such gain from optionality in the case of the good security.[22] This creates a trade-off between the good security's higher mean return versus the gains from limited liability for the bad security.

The bank faces an incentive constraint that 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

[22]The bank has the (put) option to sell its asset at strike price $\overline{\omega}_{t+1}^j$.

with Lagrange multiplier, κ_t)

$$(1-p_t)E_t^{NR}\left[\Lambda_{t,t+1}R_{t+1}^K(\theta\lambda_{t+1}^j(1-L_{D,t+1})+1-\theta)(1-e^{\frac{-\psi}{2}}-\tilde{\pi}_{t+1}^j)\right]=p_tE_t^R\left[\Lambda_{t,t+1}R_{t+1}^K(e^{-\frac{\psi}{2}}-\overline{\omega}_{t+1}^j+\tilde{\pi}_{t+1}^j)\right] \tag{32}$$

for which the derivations are found in Appendix C. The LHS illustrates the trade-off between the higher mean return of the 'good' security and the upside risk of the bad. This is the relevant consideration if there is no run next period. 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.[23]

In addition to the incentive constraint, we recall the participation constraint (18), required 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 participation and incentive constraints do not depend on bank-specific characteristics. Thus, the optimal choice of leverage is independent of net worth (as shown in the Appendix C). Therefore, we can sum across individual banks to obtain the appropriate conditions in terms of aggregate values. Banks' aggregate demand for assets depends on leverage and net worth:

$$Q_tS_t^B = \phi_tN_t \tag{33}$$

Bank net worth evolves as follows: In the absence of a run, incumbent banks retain their earnings. A run eradicates the net worth of the incumbent banks, so that $N_{S,t} = 0$ 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:

$$N_{S,t} = \max\{R_t^KQ_tS_{t-1}^B - R_t^D\Pi_t^{-1}D_t, 0\}, \qquad \text{and} \qquad N_{N,t} = (1-\theta)\zeta S_{t-1}, \tag{34}$$

where $N_{S,t}$ and $N_{N,t}$ are the net worth of incumbent and new banks, respectively. Aggregate net worth N_t is given as $N_t = \theta N_{S,t} + N_{N,t}$.

[23]Nevertheless, this channel increases the risk-shifting incentives, which then counteracts the leverage accumulation via the incentive constraint to some extent.

Endogenous Runs and Multiple Equilibria. There are occasional runs on the banking sector, in which depositors stop rolling over their deposits. 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). The endogenous element is that the existence of the run equilibrium depends on the aggregate state and especially on the balance sheet strength of the banks.

During normal times - that is in the absence of a run - 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, so that $N_{S,t} = 0$. Households cease to roll over their deposits in a run, requiring banks to liquidate their entire assets to repay the households - leaving only households (and the newly entering banks, who are quantitatively small and constrained) demanding securities. Subsequently, 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. The wedge in the household's Euler equation for securities investment is active and 'large'.

The firesale price $Q_t^\star$ is so low as to suppress the 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:

$$x_t^\star \equiv \frac{[(1-\delta)Q_t^\star + Z_t^\star]S_{t-1}^B}{\bar{R}_{t-1}D_{t-1}} < 1. \tag{35}$$

The variable $x_t^\star$ partitions the state space into a safe region without runs ($x_t^\star > 1$) 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 $x_t^\star > 1$, banks can cover the claims under the fundamental *and* firesale price.[24] 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.*

In the case of multiple equilibria, a sunspot shock selects the equilibrium, following Cole and Kehoe (2000).[25] The sunspot signals 'run' with probability Υ and 'no run' with probability $1 - \Upsilon$. If it signals

[24]Note that in the safe region, $x_t^\star$ is only indicative of that 'safety' - it does not imply the bank pays back more than the promised face value - the deposits remain debt claims, not equity.

[25]An alternative to the sunspot shock would be to use a global games (Morris and Shin (1998)) approach to determine the equilibrium. Ikeda and Matsumoto (2021) use global games in a framework with runs. Ahnert et al. (2023) apply global games in an analysis of CBDC and financial stability.

run *and* $x_t^\star < 1$, a run takes place.

Taken together, 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:

$$p_t = \text{prob}(x_{t+1}^\star < 1)\Upsilon. \tag{36}$$

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

In the presence of CBDC, it becomes especially important to account carefully for 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

$$G + \frac{R_{I,t-1}}{\Pi_t} B_{t-1} = T_t + B_t + T_{CB,t} \tag{37}$$

where G denotes government spending, T_t captures lump sum transfers from households, and $T_{CB,t}$ references lump sum remittance transfers from the central bank to the government. We assume that government spending G is constant. Since bonds are assumed in zero-net supply, we have:

$$G = T_t + T_{CB,t} \tag{38}$$

That is, CB 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. An important decision in the issuance of CBDC (and cash) is the use its of funds. We assume that the central bank uses the funds from issuance to purchase securities issued by firms at the market price[26]

$$Q_t S_{CB,t} = Ca_t + D_{CB,t} + N_{CB,t} \tag{39}$$

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

The central bank's net worth $N_{CB,t}$ evolves according to:

$$N_{CB,t} = (Z_t + (1-\delta)Q_t)S_{CB,t-1} - \Pi_t^{-1}\left[Ca_{t-1} + R_{CB,t-1}D_{CB,t-1}\right] - T_{CB,t} + N_{CB,t-1} \tag{40}$$

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 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. We assert that there is a utility loss arising from either investing directly in securities, specified by equation (10). 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 lumpsum the funds from liability issuance to households.[27] 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 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). Provided the central bank can reinvest deposits instantaneously (and there is no capital flight to non-CBDC accounts), such a policy would prevent runs completely. Notwithstanding, there are significant practical complications with this proposal, not least which banks to invest in and under what terms. Moreover, if such a policy is expected it could engender significant moral hazard. We note, of course, that such a policy is only offered as a useful benchmark or thought experiment by Brunnermeier and Niepelt (2019).

[27] The argument also requires that $S_{H,t} > S_{CB,t}$ always holds in equilibrium, which we verify numerically in our simulations.

3.4.3. Monetary policy

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

$$R_{I,t} = \max\left[R_I\left(\frac{\Pi_t}{\Pi}\right)^{\kappa_\Pi}\left(\frac{\varphi_t^{mc}}{\varphi^{mc}}\right)^{\kappa_y}, R^{LB}\right], \tag{41}$$

where deviations of marginal costs from its deterministic steady state φ^{mc} capture the output gap (Gali and Gertler (1999)). We explicitly acknowledge a constraint imposed by the zero lower bound R^{LB}.[28]

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, (5), the associated Euler equation for households is

$$1 = \beta E_t\left[\Lambda_{t,t+1}\Pi_{t+1}^{-1}R_{I,t}\right] \tag{42}$$

Combining this expression with the Euler equation for balances of CBDC, we obtain a relationship between $R_{I,t}$, $R_{CB,I}$ and $D_{CB,t}$

$$R_{CB,t} = \left(1 - L_{D,t}\right)R_{I,t} \tag{43}$$

Since $R_{I,t}$ is tied to the operation of the Taylor rule, this equation defines a locus of $R_{CB,t}$ and $D_{CB,t}$ values that must be respected. 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.[29]

[28]As discussed below, we exploit the flexibility that our global solution method permits, in various aspects of the paper. The role of CBDC in alleviating the zero lower bound has been discussed in various circles for some time (see Agarwal and Kimball (2015)) and we envisage applying our framework to such debates in ongoing work, particularly in regard to the reversal rate (see Darracq Pariès et al. (2023)) given our emphasis on banks.

[29]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 this paper.

3.4.4. Closing the model

The aggregate resource constraint is

$$Y_t = (1 + s_t)C_t + I_t + G_t + \frac{\psi_m}{2} Ca_t^2 + \frac{\rho^r}{2} \left(\frac{\Pi_t}{\Pi} - 1 \right)^2 Y_t, \tag{44}$$

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

4.1. Mapping Model to the Data

We calibrate the model to the euro area using quarterly data from 2000:Q1 to 2023:Q4, as well as our survey on German households. The parameters can be divided into three subsets: conventional parameters, parameters related to money holdings, and parameters governing the banks. To inform the latter subsets, we match selected moments related to money holdings and the banking sector. Table 3 summarizes the parameterization, sources, and chosen data moments.

The discount factor β is set to 0.995, which provides a 2% real interest rate. The risk aversion σ^H is 1 to have a logarithmic utility function for consumption, while the Frisch labor elasticity $1/\varsigma$ 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, which is in line with the euro area data. 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. (Forthcoming). 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. (2024). 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 – that is satiation in money-holdings is not obtained. This has the additional benefit 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 a CBDC to cash ratio of 0.56 in normal times, under the baseline. Thus, we target this ratio in the risky steady state (RSS) setting $\mu_{cb} = 0.86$.[30] Under the optimistic scenario, we target a ratio of 1.17. 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 relate to the banking sector. We use the asset share of households to target the claims to non-financial firms to GDP ratio in the euro area. We aim for a leverage ratio of around 15.5, which implies a capital requirement of 6.5% by setting the mean of the substandard security. The intermediation cost of households 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 with 1.5% in a year (every 66.7 years). The survival rate and the persistence of the volatility shock are set following Rottner (2023). The parameter calibrating the initial net worth of new banks ζ follows from setting the other parameters. The standard deviation of the volatility shock targets the standard deviation of bank capital (net worth). 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

[30] 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.

Parameters		Value	Target / Source
		a) Conventional parameters	
Discount factor	β	0.995	Risk free rate = 2.0% p.a.
Frisch labor elasticity	$1/\varphi$	0.75	Conventional
Risk aversion	σ^H	1	Logarithmic utility function
TFP level	A	0.407	Output normalization
Labor disutility	χ	1	Normalization
Government spending	G	0.2	Govt. spending to GDP ratio
Capital share	α	0.33	Capital income share
Capital depreciation	δ	0.025	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	0.25	Bernanke et al. (1999)
Investment parameter 1	a_1	0.530	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	0.125	Literature
		b) Parameters related to money	
Transaction cost parameter 1	s_1	0.04	Currency to GDP ratio
Transaction cost parameter 2	s_2	10^{-4}	Falling money demand
Storage cost cash	ψ_m	0.002	Burlon et al. (Forthcoming)
CES elasticity	η_m	6.6	Di Tella and Kurlat (2021)
Weight deposits	μ_d	0.21	Spread between policy and deposit rate
Weight CBDC baseline scenario	μ_{cb}	0.86	Conducted household survey
Weight CBDC keen scenario	μ_{cb}	0.98	Conducted household survey
		c) Banking sector & shocks	
Parameter asset share HH	γ^F	0.33	Claims against non-financial firm's to GDP ratio
Mean substandard security	ψ	0.01	Bank capital level
Intermediation cost HH	Θ	0.04	Financial crisis probability
Survival rate	ζ	0.88	Rottner (2023)
Persistence volatility	ρ^σ	0.96	Rottner (2023)
Std. dev. volatility shock	σ^σ	0.001	Stdandard deviation of bank capital
Sunspot Shock	Υ	0.50	GDP response during run

Table 3: Calibration and Targeted Moments

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-sized 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 $\mathbb{X} = \{S, N, \sigma, \iota\}$ and 8 policy functions

$\mathbb{Y} = \{Ca, D_b, D_{cb}, C, Q, \bar{b}, \lambda, \pi\}$ 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. This results in a doubling of policy functions, that is 16 instead of 8 in our context, that must be obtained. Furthermore, to incorporate the possibility of an endogenous run, we additionally solve for the law of motion of net worth $N'(\mathbb{X}, \sigma', \iota')$ and the probability of a run next period $P(\mathbb{X})$. These objects are conditioned on the shock realizations next period, resulting in substantially increased computational burden.[31]

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.

5.1. Endogenous runs and the role of CBDC

We describe how a run on the banking sector evolves in the model. To outline the dynamics, figure 6 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.[32] 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': calm times sow the seeds for later crises (see Adrian and Shin (2010) and Brunnermeier 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. The sunspot shock selects either the run equilibrium (blue solid line) or the equilibrium without run (red dashed line).

[31] Appendix D contains the details on the numerical solution procedure.

[32] Recall, even if the recovery ratio is less than unity and multiple equilibria exist, a run will only occur if the sunspot shock takes a particular value. As noted in Gorton and Ordonez (2020), not every boom ends in a bust.

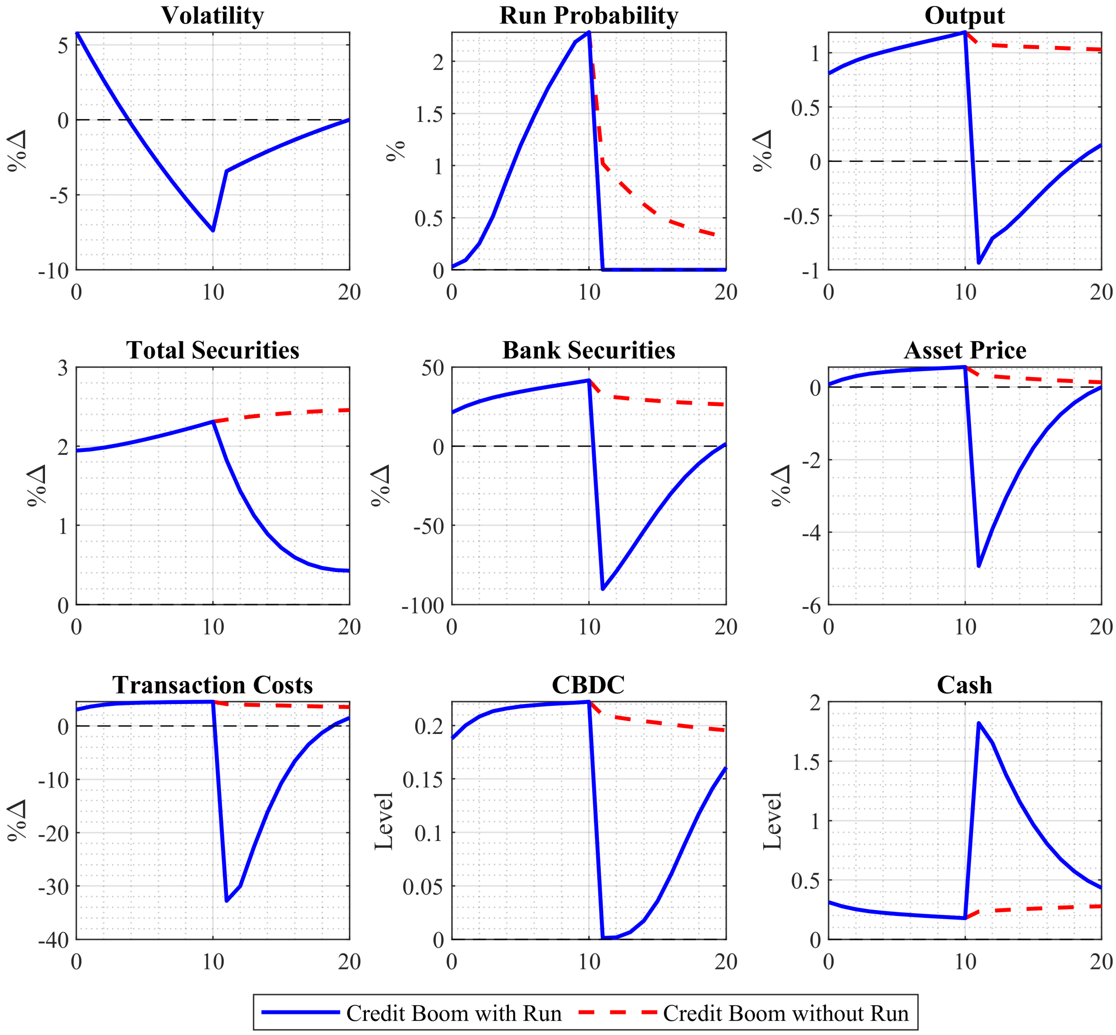

Figure 6: Impulse response of the economy to a sequence of volatility shocks. The economy is initially at the risky steady state. Then a sequence of one-standard-deviation negative shocks materializes in period 1 until period 10. The economy is then hit by a two-standard-deviation positive volatility shock in period 11, moving the economy into a fragile region with multiple equilibria. A sunspot shock realized in period 11 selects the run equilibrium. 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.

In figure 6, 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.[33] 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

[33] Recall that, we assume that central bank and households are equally inefficient at investing (setting $\Theta_{CB} = 1$). Equivalently, households internalize the welfare cost of central bank investment.

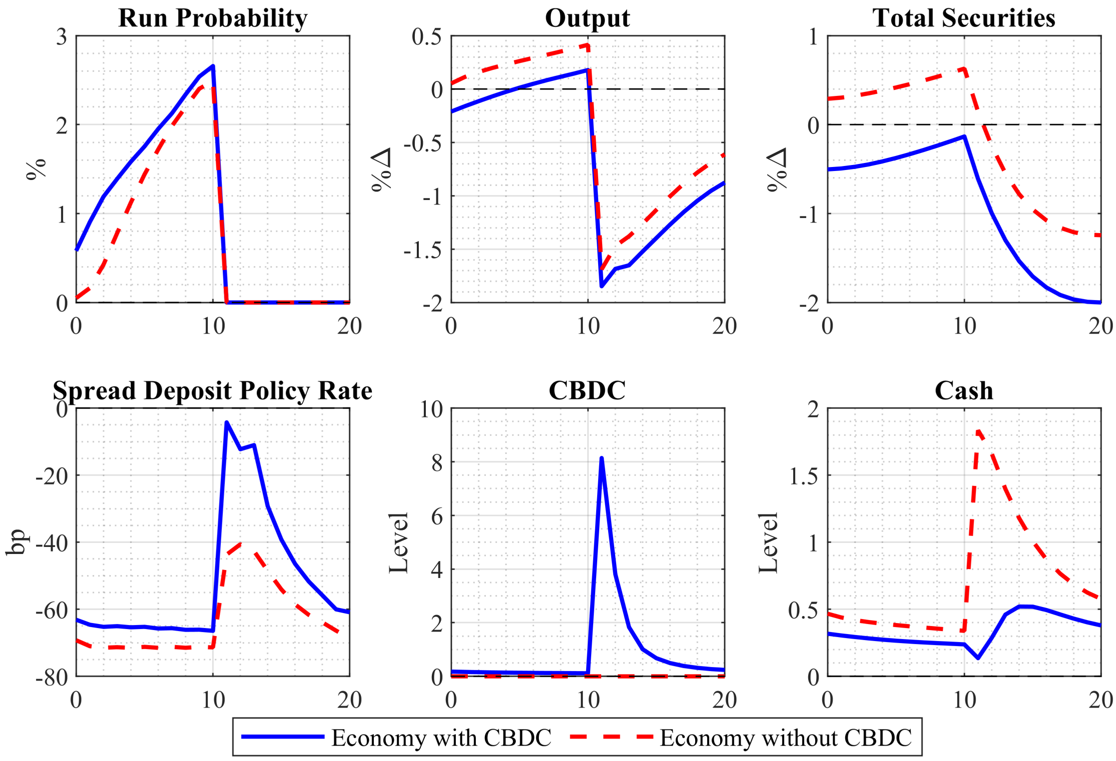

Figure 7: Comparison between an economy with CBDC (blue solid) and without CBDC (red dashed) during a credit boom gone bust. The sequence of shock is the same as in Figure 6. The scales are either percentage deviations from the risky SS (%Δ), annualized percent (%), annualized basis points (bp), or level.

'fast' disintermediation. Indeed, CBDC demand is sufficiently high that there is a temporary fall in cash holdings since 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 7 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. The diagram also points to elements of the 'slow disintermediation' we will discuss in further detail below. We note that in the pre-run periods, 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 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.

5.2. Slow and Fast Disintermediation

To disentangle the channels through which CBDC affects the economy, we compare different setups. Specifically, table 4 reports how design choices for the monetary system affect financial stability and other economic outcomes, along with household welfare, expressed as 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, 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 4 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 7.[34]

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. It seems reasonable to assume that it will be convenient (cheap and fast) to move and store large amounts of CBDC. In contrast, it is inconvenient (costly, slow and dangerous) to hold large amounts of cash. This is reflected in our specification of equation 4, and its parameterization (following Burlon et al. (Forthcom-

[34]While liquidity premia are important mainly to understand slow disintermediation, the premia also play a (small) role in times of runs. To understand the role of liquidity premia in 'fast' disintermediation, we simulate the model and examine average outcomes in times of runs. The spread narrows in both cases (no CBDC and CBDC) to almost zero, though slightly more in the CBDC case.

ing). The ‘storage at scale channel’ facilitates ‘fast’ disintermediation, as it is more attractive to run on the banking sector. 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.

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 0.14% higher in the absence of CBDC, measured in consumption equivalents. Furthermore, the probability of observing a run is almost 50% lower (1.34% vs 2.51%) in the absence of CBDC. In other words, a run 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 scenarios. Based on the keen respondents to our survey, we consider a scenario with $\mu_{cb} = 0.98$. That is, we increase the weight of CBDC in the money aggregator is larger, matching the higher implied 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 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 that any model of CBDC is at this point quite tentative, it is perhaps useful to analyse a broader set of parameterizations. In particular, given uncertainty over CBDC adoption we explore how varying the weight parameter, μ_{cb}, in the money aggregator affects the results. This parameter maps fairly directly to demand for CBDC.

We find that welfare gains increase with μ_{cb}. A key reason is that a higher demand for CBDC enhances ‘slow’ disintermediation via the ‘liquidity premium channel’. 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 8, the introduction of CBDC can have positive welfare effects for sufficiently high values of μ_{cb}, though these would imply ‘counterfactually’ high

	Base CBDC $\mu_{cb} = 0.86$	No CBDC $\mu_{cb} = 0$	Keen CBDC $\mu_{CB} = 0.98$	CBDC Costs $\psi_{cb} = 0.2\%$	No run $\Upsilon = 0$ CBDC	No CBDC
Key moments						
Welfare W (CE)[a]	–	0.14	0.04	0.12	0.334	0.329
Run probability[b]	2.51	1.34	2.20	1.55	0	0
Risky steady state[c]						
CBDC D_{CB}	0.18	0	0.27	0.15	0.18	0
Cash Ca	0.32	0.47	0.23	0.33	0.32	0.48
Deposit D	3.51	3.53	3.48	3.50	3.48	3.52
Money M	1.23	1.17	1.27	1.22	1.24	1.18
Transaction cost $s(v)$	1.79%	1.88%	1.72%	1.80%	1.78%	1.87%
Spread $R_D - R_I$ (bp)	−63.1	−69.2	−58.9	−64.1	−62.2	−68.3
Total Securities S	9.07	9.14	9.04	9.09	9.13	9.17
Share Banks S_B/S	41.4%	41.3%	41.1%	41.1%	40.7%	41.0%
Average value during run period[d]						
CBDC D_{CB}	7.86	0	7.34	1.05	–	–
Cash Ca	0.14	1.832	0.11	1.21	–	–
Deposit D	0.23	0.25	0.23	0.24	–	–
Money M	6.97	1.92	7.52	2.44	–	–
Transaction cost $s(v)$	0.2%	0.11%	0.2%	0.9%	–	–
Spread $R_D - R_I$ (bp)	0.0	-0.1	0.0	-0.1	–	–
Average (non-run and run periods)[e]						
CBDC D_{CB}	0.31	0	0.39	0.17	0.19	0
Cash Ca	0.32	0.49	0.24	0.35	0.33	0.49
Deposit D	3.32	3.42	3.31	3.38	3.45	3.50
Money M	1.32	1.18	1.36	1.24	1.24	1.18
Transaction cost $s(v)$	1.75%	1.87%	1.69%	1.79%	1.78%	1.87%
Spread $R_D - R_I$ (bp)	−61.9	−69.2	−58.1	−63.9	−62.7	−68.7
Total Securities S	9.00	9.09	8.98	9.04	9.11	9.16
Share Banks S_B/S	39.4%	40.2%	39.3%	39.9%	40.5%	40.8%

[a] Welfare change expressed as consumption equivalent relative to baseline with 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 4: Welfare, financial stability and economic outcomes of various policies

preference for CBDC. The figure shows that introducing CBDC becomes welfare-improving at a level of $mu_{cb} = 1.28$, implying a demand for CBDC that is double that in our baseline parameterization and 1.5 times that of our keen parametrization. Additionally, the amount of cash would be very low as the CBDC to cash ratio is around five.

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. It is not unreasonable to think that with further technological developments, structural parameters relating to transactions benefits of digital money will continue to move in favor of CBDC. A related question then, of course, is how other digital moneys - be they traditional bank deposits or more novel forms, such as stablecoin or tokenized deposits - will fare. This is beyond the scope of our paper, but will need to be discussed in a structural DSGE framework of the sort we have offered.

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. In early discussions of CBDC there was frequent reference to remuneration as a useful policy tool (see Bindseil (2020), Bindseil and Panetta (2020) and Barrdear and Kumhof (2022) for example) and, in some cases, a way of implementing negative rates. However, in recent years, perhaps for reasons related to complexity of implementation and the continued commitment to issuing cash (implying an enduring zero lower bound), these debates have subsided somewhat. Nevertheless, it is conceptually worthwhile to consider the implications of remuneration for CBDC demand and financial stability. We begin this section, though, with a much more pressing topic - that of holding constraints, which appear likely to feature in any initial implementation of a CBDC.

6.1. Holding Limits

It has been commonly suggested that there should be a limit on how much CBDC can be held. Typically the argument is motivated by concerns of 'fast disintermediation'. As such, our framework is ideally suited to considering this concern. 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

$$D_{CB,t} \leq \overline{D}_{CB} \tag{45}$$

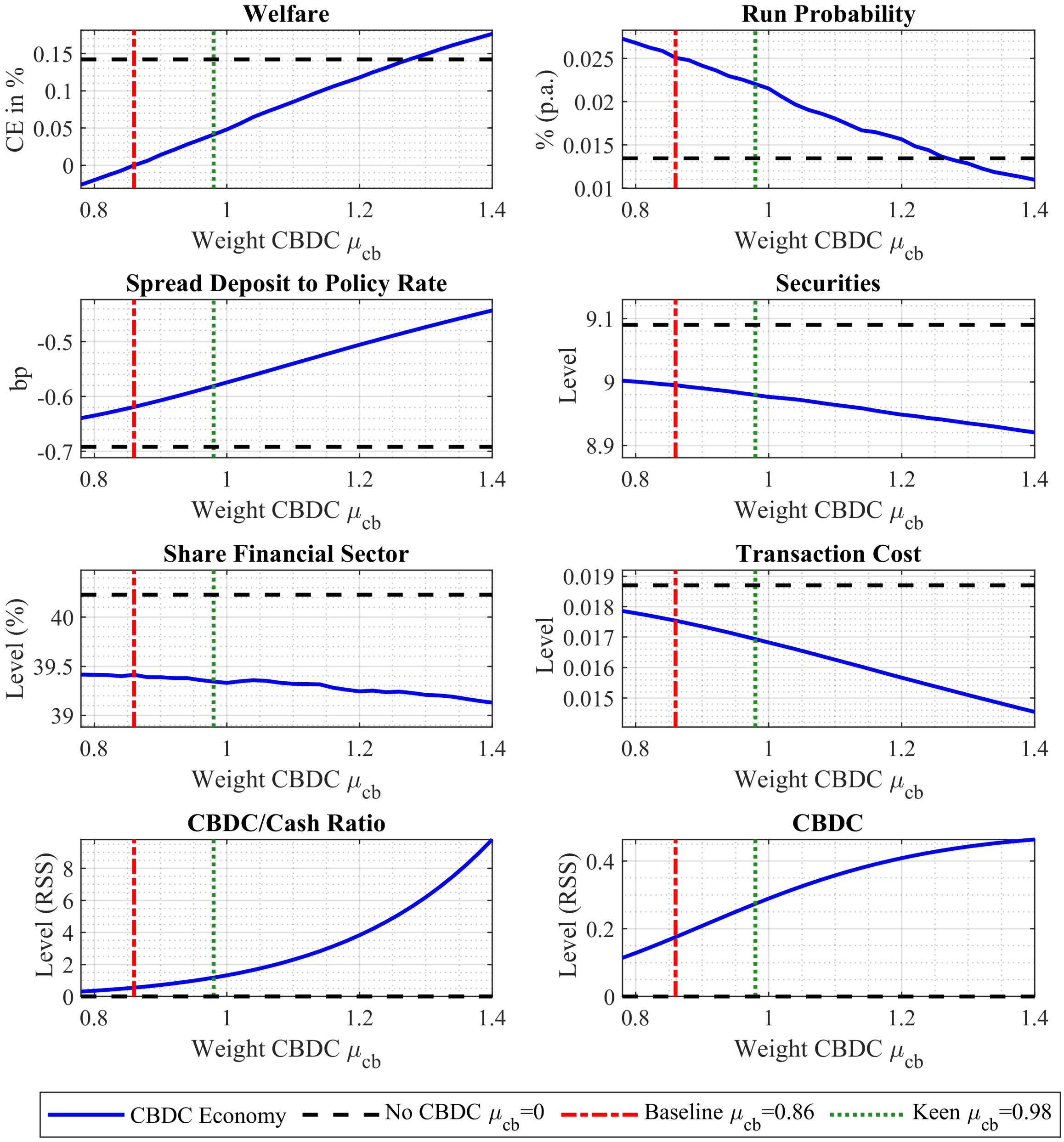

Figure 8: Impact of variations in the weight of CBDC μ_{cb} in the money aggregator on the equilibrium (blue line). Baseline scenario (red dash-solid), keen scenario (green footed) and no CBDC scenario (black dashed) are highlighted. Most variables display their mean. CBDC-cash-ratio and CBDC values 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).

The first order condition that determines the CBDC demand, equation (13) originally, now becomes

$$1 + \overline{\mu}_{CB,t} = \beta E_t \left[\Lambda_{t,t+1}\Pi_{t+1}^{-1}\right] R_{CB,t} + \frac{\varphi_t}{\varrho_t}\mu_{cb}\left(\frac{M_t}{D_{CB,t}}\right)^{\frac{1}{\eta_m}} \tag{46}$$

where $\overline{\mu}_{CB,t}$ is the normalized multiplier associated with the new constraint. If the constraint is not binding, then $\overline{\mu}_{CB,t} = 0$, and the equation is the same as before. However, if the constraint is binding

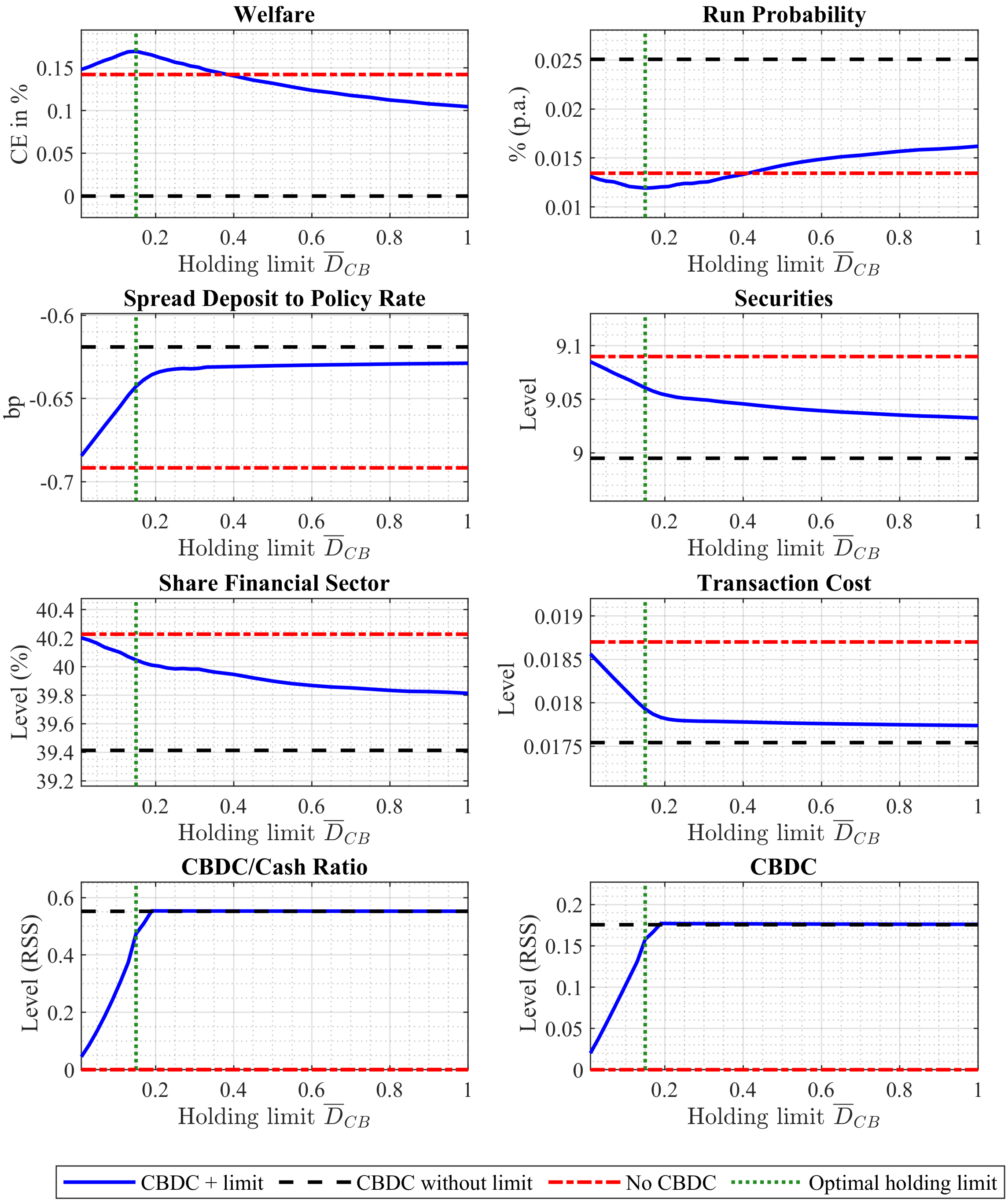

Figure 9: Impact of holding limits for CBDC $\overline{D}_{CB}$ on the equilibrium (blue line) for the base scenario $\mu_{cb} = 0.86$. The horizontal lines show CBDC without limit (black dashed) and the economy without CBDC for comparison. Most variables display their mean. CBDC-cash-ratio and CBDC 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).

- and in the equilibria and parameterization we consider it *will* occasionally bind - then $\overline{\mu}_{CB,t} > 0$ (households would like to increase their holdings beyond the limit but are unable).

Clearly, holding limits contain the 'storage at scale channel' as it becomes impossible to hold and store large shares of the typical portfolio in CBDC. However, the trade-off for such a limit is that depending on its level, it can also affect CBDC holdings in normal times. If the limit is above the average holdings, the effects on 'slow' disintermediation is negligible.[35] The liquidity premium in normal times is correspondingly effectively unchanged. 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 9 shows how a limit affects financial stability, economic outcomes, and welfare. In our model, the optimal holding limit is around €1500 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. To get a better understanding of the potential values of the optimal holding We repeat the same analysis for our 'keen' parameterization. In this case, the model suggests an optimal value of around €2500.[36]

Our quantitative model thus suggests values 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.[37]

6.2. Remuneration of CBDC

We now consider the case where the CBDC is remunerated. We allow the remuneration to depends on the nominal riskless rate on non-money assets, where the latter is pinned down by a Taylor rule, as aforementioned. The relationship between the two interest rates is described by a simple rule. Specifically, we assert that the central bank moves the rates in lock step, but with a wedge between the two. This is somewhat akin to how benchmark rates are typically moved in relation to each other (such as the floor

[35]The model is fully rational and nonlinear so there will be *some* effect even if the limit is introduced in an economy where it ostensibly is not binding in normal times.

[36]Additional results can be found in Appendix F.

[37]There are interesting debates over the setting of limits and, in the case of the UK, it has been suggested that a limit might be set in the £10,000 - £20,000 range, partly to allow for salary payments to be easily accommodated (see Panetta (2023c)). We are currently exploring model extensions that explore heterogeneity in CBDC demand across households, and Muñoz and Soons (2023) features a model with a two types of agents exhibiting fixed heterogeneity in beliefs about bank stability.

and ceiling of a corridor, or RRP and IOER in recent times in the US):[38]

$$R_{CB,t} = R_{I,t} - \Delta_{CB} \tag{47}$$

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 then negative.

It transpires that 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 10 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 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, limiting the 'fast' disintermediation.

As the figure already suggests, remunerated CBDC performs well in terms of welfare and financial stability. Welfare increases by 0.21% and the run probability drops to 0.98. Indeed, remunerated CBDC outperforms unremunerated CBDC *with optimal holding limits*.

There are two 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). If the central bank abstains from negative rates, this change affects the results substantially. We model this by imposing an occasionally binding lower bound that ensures a non-negative remuneration

[38]Of course, one could imagine policy introducing variation in the wedge between $R_{I,t}$ and $R_{CB,t}$, depending on the state of the economy, but we leave a more detailed treatment for future work.

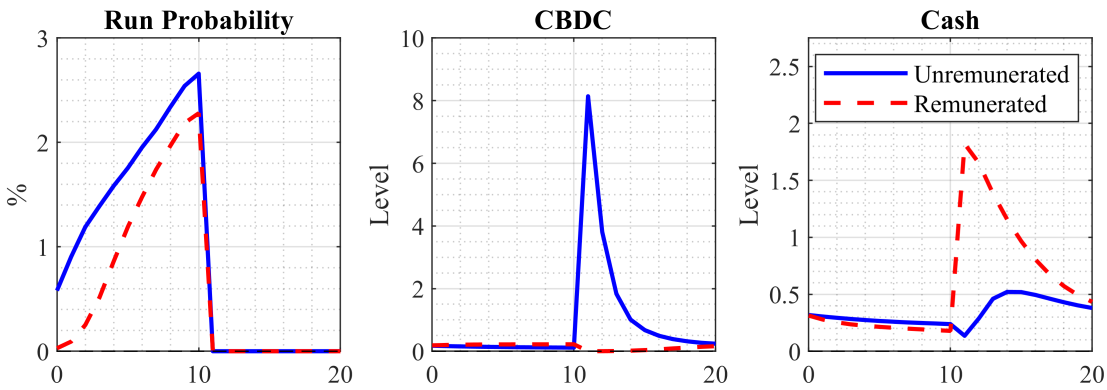

Figure 10: Comparison between an economy with unremunerated CBDC (blue solid) and remunerated CBDC (red dashed) during a credit boom gone bust. The sequence of shock is the same as in Figure 6. The scales are either annualized percent (%) or level.

rate on CBDC

$$R_{CB,t} = \max\left[R_{I,t} - \Delta_{CB}, 1\right] \tag{48}$$

Once negative remuneration is excluded, households can again exploit the 'storage of scale' of CBDC and shift large shares of their portfolio to CBDC during a run. Even though there are slight gains from increased 'slow' disintermediation during a boom, the general effect is small. Financial stability and welfare are almost the same as in our baseline scenario with unremunerated CBDC.

The second caveat is that the monetary authority must immediately offer a negative remuneration during the onset of a run. If there were any lag or some mistake in setting the remuneration rate, 'fast' disintermediation could become a challenge again. Thus, our results about the gains of remuneration could be interpreted as an upper bound. 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

In the absence of data on actual CBDC usage in Europe, and in the presence of complicated general equilibrium effects, the combination of hypothetical survey evidence and a structural macroeconomic model is a powerful one. It allows us to think about a CBDC's implications, under different assumptions for policy, and thus helps plan its trials and, perhaps, eventual roll-out. We have offered 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 - factors such as inflation expectations and wealth seem to be somewhat influential, but in particular 'trust' seems to play an important role.

The 'slow' and 'fast' disintermediation implied by our survey results are often debated in discussions over the digital euro and other CBDCs. We offer a structural macroeconomic model that features both phenomena and show that they interact in interesting and important ways. 'Slow' disintermediation appears to have a beneficial effect on financial stability by shrinking a fragile banking system, and CBDC in this sense makes a positive contribution to welfare. However, there is an offsetting effect if it is introduced in isolation, which is its tendency to increase run risk, or 'fast' disintermediation, which overall makes CBDC's welfare contribution negative. Nevertheless, by introducing CBDC along with judicious holding limits, allows the benefits of 'slow' disintermediation to be retained, while reducing its effect on 'fast' disintermediation, yielding welfare gains overall. While the model is still somewhat stylized - and while there is important work still to be done in modeling the central bank's balance sheet and influence on intermediation - we offer the first medium scale DSGE model, empirically disciplined, that can encompass key debates over CBDC's effect on the banking system.

The implications of our findings are broad. As Stein (2013) has noted, monetary policy actions are capable of 'getting in the cracks' of financial markets. Monetary policy can influence financial stability without leaving loopholes or being prone to regulatory arbitrage. Many resource-costly regulatory schemes are implemented to offset the fact that banks are arguably too big and too levered. In this context, a policy that has the sort of slow-disintermediating effect that CBDC does in our model, may play an important financial stability role. However, a richer model would be needed to make this point more formally and we leave this for future work.

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Appendix A. 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 Results Survey

We provide below several additional results from the survey.

Q2 \ Q3	+25bp	0bp	-25bp
dEUR	99.7	97.6	70.0
No dEUR	48.1	22.8	7.1

Table B.5: Percent of respondents who project positive holdings of dEUR in Q3 at different rates of remuneration, conditioning on answer in Q2 (first number in row for given column pair is the percent projected to hold dEUR)

Sample	ECBpref	Hightrust	Lowtrust	Aware	Highinf	Lowinf	Highinc	Lowinc	Highnw	Lownw	Highdep	Lowdep	Young	Old	Transact	Unbanked	Investor	Educ	Male
All	50	28	20	92	29	20	18	2	11	32	15	14	18	45	59	5	93	27	59
Keen	61	35	11	93	26	21	16	2	11	30	12	14	20	40	59	4	92	28	58
Open	52	30	17	92	28	21	18	2	11	31	14	14	19	44	59	4	93	27	59
Hater	33	16	37	90	38	16	19	2	11	35	18	19	12	49	62	4	94	25	62

Table B.6: Fractions of different sample populations with particular characteristics. All: All respondents. Keen: Positive unremunerated dEUR in steady state (Q2). Open: Keen, or holds positive reumunerated dEUR with rate of remuneration equal to or 25 bp above current account rate (Q3), or positive unremunerated dEUR in times of bank stress (Q5). Hater: Zero remunerate dEUR even when offered 25 bp above current account rate (Q3).

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

	Unremunerated	Remunerated	Stress
Highinc	-0.040***	-0.003	-0.025**
	(-3.936)	(-0.303)	(-2.313)
Lowinc	0.057**	-0.041	-0.024
	(1.970)	(-1.481)	(-0.791)
Highnw	-0.022**	-0.003	-0.048***
	(-2.169)	(-0.267)	(-4.453)
Lownw	0.072***	0.061***	0.015
	(5.389)	(4.835)	(1.050)
Highdep	-0.126***	-0.101***	-0.102***
	(-10.175)	(-8.476)	(-7.526)
Lowdep	0.003	-0.005	-0.027**
	(0.267)	(-0.534)	(-2.403)
Highinf	-0.028***	-0.009	-0.065***
	(-3.212)	(-1.067)	(-7.159)
Lowinf	-0.004	0.011	0.012
	(-0.430)	(1.231)	(1.213)
FS	-0.017**	-0.008	0.103***
	(-2.424)	(-1.210)	(14.135)
Transact	0.029***	0.006	0.005
	(3.775)	(0.861)	(0.667)
Unbanked	-0.126***	-0.152***	-0.188***
	(-3.346)	(-4.068)	(-4.363)
Investor1	-0.044***	-0.031**	-0.030**
	(-3.286)	(-2.412)	(-2.175)
Educ	0.014*	-0.008	0.026***
	(1.803)	(-1.090)	(3.125)
East89	-0.036***	-0.025*	-0.052***
	(-2.695)	(-1.950)	(-3.715)
Young	-0.005	0.026***	0.086***
	(-0.517)	(2.731)	(8.610)
Old	-0.069***	-0.012	-0.017**
	(-8.641)	(-1.597)	(-2.075)
Male	-0.004	-0.012	-0.070***
	(-0.472)	(-1.602)	(-8.505)
Hightrust	0.076***	0.078***	0.105***
	(9.351)	(10.213)	(12.731)
Lowtrust	-0.218***	-0.188***	-0.228***
	(-22.726)	(-20.023)	(-22.356)
remun+25		0.158***	
		(16.823)	
remun-25		-0.226***	
		(-25.394)	
remun-50		-0.208***	
		(-23.196)	
N	19140	19140	19140

z statistics in parentheses

Note: Table displays marginal effects.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B.8: Intensive regressions: All sample

	Unremunerated	Remunerated	Stress
Highinc	0.054	1.259	-0.942
	(0.038)	(0.814)	(-0.506)
Lowinc	-4.203	-3.034	-9.589**
	(-1.607)	(-0.719)	(-2.005)
Highnw	2.462*	3.016*	0.945
	(1.738)	(1.912)	(0.493)
Lownw	0.310	0.484	1.433
	(0.171)	(0.255)	(0.578)
Highdep	3.749*	4.504**	5.392**
	(1.908)	(2.246)	(2.008)
Lowdep	1.690	2.804*	4.024*
	(1.163)	(1.744)	(1.930)
Highinf	1.376	2.816**	-1.184
	(1.138)	(2.125)	(-0.706)
Lowinf	0.410	0.860	0.288
	(0.336)	(0.656)	(0.169)
FS	-1.524	-0.681	5.088***
	(-1.570)	(-0.649)	(3.879)
Transact	0.287	-0.105	1.029
	(0.265)	(-0.091)	(0.685)
Unbanked	0.152	1.692	-0.217
	(0.030)	(0.260)	(-0.019)
Investor1	1.913	2.263	3.357
	(1.193)	(1.339)	(1.451)
Educ	-0.810	-1.057	1.192
	(-0.795)	(-0.942)	(0.810)
East89	2.869	2.635	-3.658
	(1.116)	(1.020)	(-1.388)
Young	-4.057***	-1.483	0.304
	(-3.471)	(-1.077)	(0.168)
Old	2.744**	1.500	2.986*
	(2.272)	(1.238)	(1.958)
Male	-0.586	-0.846	0.527
	(-0.529)	(-0.713)	(0.348)
Hightrust	1.259	2.238**	4.230***
	(1.185)	(2.009)	(2.993)
Lowtrust	-2.091	-0.148	1.892
	(-1.139)	(-0.072)	(0.716)
remun+25		8.843***	
		(6.088)	
remun-25		-9.655***	
		(-6.736)	
remun-50		-8.795***	
		(-6.139)	
N	1299	1297	1304
R^2	0.038	0.163	0.033

z statistics in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B.9: Trust (Probit): Full sample

	High trust	Low trust
Highinc	-0.024	-0.000
	(-1.144)	(-0.023)
Lowinc	0.145**	-0.022
	(2.206)	(-0.503)
Highnw	-0.020	0.046**
	(-0.962)	(2.484)
Lownw	-0.015	0.035
	(-0.521)	(1.486)
Highdep	-0.050*	0.060***
	(-1.927)	(2.604)
Lowdep	0.005	0.047**
	(0.227)	(2.485)
Highinf	-0.132***	0.161***
	(-7.936)	(9.480)
Lowinf	0.084***	-0.008
	(4.326)	(-0.505)
Transact	0.008	0.010
	(0.495)	(0.783)
Unbanked	-0.129*	0.099
	(-1.808)	(1.310)
Investor1	-0.034	0.004
	(-1.173)	(0.188)
Educ	0.034**	-0.042***
	(2.028)	(-3.283)
East89	-0.080***	0.095***
	(-3.110)	(3.712)
Young	-0.032	-0.003
	(-1.622)	(-0.161)
Old	-0.056***	0.012
	(-3.454)	(0.864)
Male	-0.003	0.085***
	(-0.195)	(6.829)
Bigcity	0.021	0.006
	(1.255)	(0.430)
Smallpop	-0.010	-0.015
	(-0.480)	(-0.854)
N	3828	3828

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

$$V_t(N_t^j) = \max_{\{\phi_t^j,\bar{b}_t^j\}} (1-p_t^j)\beta E_t^N \Lambda_{t,t+1}\left[\theta V_{t+1}\left(\Big(1 - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}\Big) R_{t+1}^K \phi_t^j N_t^j\right) + (1-\theta)\big(1 - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}\big) R_{t+1}^K \phi_t^j N_t^j\right]$$

$$+ \lambda_t^j\left[(1-p_t^j)\beta E_t^N[\Lambda_{t,t+1}\phi_t^j N_t^j \bar{b}_t^j \Pi_{t+1}^{-1}] + p_t^j\beta E_t^R[R_{t+1}^K \phi_t^j N_t^j] - (\phi_t^j N_t^j - N_t^j)\left[1 - \frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}}\right]\right]$$

$$+ \kappa_t^j\beta\Bigg\{\Bigg[(1-p_t^j)E_t^N\Lambda_{t,t+1}\left[\Lambda_{t,t+1}\theta V_{t+1}\left(\Big(1 - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}\Big) R_{t+1}^K \phi_t^j N_t^j\right) + (1-\theta)\Big(1 - \frac{\bar{b}_t^j}{R_{t+1}^K\Pi_{t+1}}\Big) R_{t+1}^K \phi_t^j N_t^j\right]\Bigg]$$

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

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:

$$
\begin{aligned}
0 =&(1-p_t^j)E_t^N\beta\Lambda_{t,t+1}R_{t+1}^K[\theta V_{t+1}^{\prime j}+(1-\theta)](1-\overline{\omega}_{t+1}^j) \\
&+\lambda_t^j((1-p_t^j)E_t^N\beta[\Lambda_{t,t+1}R_{t+1}^K\overline{\omega}_{t+1}^j]+p_tE_t^R\beta[\Lambda_{t,t+1}R_{t+1}^K]-[1-\frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}}]) \\
&+\kappa_t^j((1-p_t^j)\beta E_t^N\Lambda_{t,t+1}R_{t+1}^K[\theta V_{t+1}^{\prime j}+(1-\theta)](1-\overline{\omega}_{t+1}^j) \\
&-\kappa_t^j\beta E_t\Lambda_{t,t+1}\int_{\overline{\omega}_{t+1}^j}^{\infty}\left[R_{t+1}^K[\theta V_{t+1}^{\prime j}+(1-\theta)](\omega-\overline{\omega}_{t+1}^j)\right]d\tilde{F}_{t+1}(\omega) \\
&-\frac{\partial p_t^j}{\phi_t^j}E_t^N\beta\Lambda_{t,t+1}R_{t+1}^K[\theta V_{t+1}^{\prime j}+(1-\theta)](1-\overline{\omega}_{t+1}^j)\left(1+\kappa_t^j\right) \\
&-\frac{\partial p_t^j}{\phi_t^j}E_t^N\left(R_{t+1}^K\overline{\omega}_{t+1}^j-R_{t+1}^K\right)
\end{aligned}
\tag{C.4}
$$

Note that we use $\overline{\omega}_{t+1}^j=\overline{b}_t^j/\left(R_{t+1}^K\Pi_{t+1}\right)$. 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

$$
\begin{aligned}
0 =&(1-p_t^j)E_t^N\beta\Lambda_{t,t+1}R_{t+1}^K[\theta V_{t+1}^{\prime j}+(1-\theta)](1-\overline{\omega}_{t+1}^j) \\
&+\lambda_t^j((1-p_t^j)E_t^N\beta[\Lambda_{t,t+1}R_{t+1}^K\overline{\omega}_{t+1}^j]+p_tE_t^R\beta[\Lambda_{t,t+1}R_{t+1}^K]-[1-\frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}}]) \\
&+\kappa_t^j((1-p_t^j)\beta E_t^N\Lambda_{t,t+1}R_{t+1}^K[\theta V_{t+1}^{\prime j}+(1-\theta)](1-\overline{\omega}_{t+1}^j) \\
&-\kappa_t^j\beta E_t\Lambda_{t,t+1}\int_{\overline{\omega}_{t+1}^j}^{\infty}\left[R_{t+1}^K[\theta V_{t+1}^{\prime j}+(1-\theta)](\omega-\overline{\omega}_{t+1}^j)\right]d\tilde{F}_{t+1}(\omega)
\end{aligned}
\tag{C.6}
$$

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

$$
\begin{aligned}
0 =&-\beta(1-p_t^j)E_t^N\Lambda_{t,t+1}[\theta V_{t+1}^{\prime j}+(1-\theta)]+\lambda_t^j\beta(1-p_t^j)E_t^N\Lambda_{t,t+1} \\
&-\kappa_t^j\beta(1-p_t^j)E_t^N\Lambda_{t,t+1}\left\{[\theta V_{t+1}^{\prime j}+(1-\theta)]\right\} \\
&+\kappa_t^j\beta(1-p_t^j)E_t\Lambda_{t,t+1}\int_{\overline{\omega}_{t+1}^j}^{\infty}\left[\theta V_{t+1}^{\prime j}+(1-\theta)\right]d\tilde{F}_{t+1}(\omega)-\theta\frac{V_{t+1}(0)}{R_{t+1}^KQ_tS_t^{Bj}}\tilde{f}_t(\overline{\omega}_{t+1}^j)
\end{aligned}
\tag{C.7}
$$

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:

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

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

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

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

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:

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

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

The first order conditions determine λ_t and κ_t:

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

$$\kappa_t = \frac{\beta(1-p_t)E_t^N\Lambda_{t,t+1}\left[\lambda_t-(\theta\lambda_{t+1}\Sigma_{t+1}+1-\theta)\right]}{(1-p_t)E_t^N\beta\Lambda_{t,t+1}\Big[(\theta\lambda_{t+1}\Sigma_{t+1}+1-\theta)\,\tilde{F}_{t+1}(\overline{\omega}_{t+1})\Big]+p_t E_t^R\beta\Lambda_{t,t+1}\Big[(\theta\lambda_{t+1}\Sigma_{t+1}+1-\theta)\Big(1-\tilde{F}_{t+1}(\overline{\omega}_{t+1})\Big)\Big]} \tag{C.15}$$

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 $V_t(N_t) = \lambda_t\Sigma_t N_t$:

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

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

We can now reformulate this as an expression for λ_t

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

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

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

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

Appendix D. 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.[39] 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.[40] 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

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

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 equilibriau (e.g. $f^1_{Ca}(\mathbb{X}_t;\Theta^P)$ and $f^2_{Ca}(\tilde{\mathbb{X}}_t;\Theta^P)$)

[39] Note that our model is more complex to solve due to the elaborated portfolio choice underpinning our model.
[40] 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.

(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

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:

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

$$\text{err}_2 = 1-\beta E_t\Lambda_{t,t+1}\frac{R_{I,t}}{\Pi_{t+1}}, \quad (D.3)$$

$$\text{err}_3 = (1-p_t)E_t^N\left[\beta\Lambda_{t,t+1}\bar{R}_tD_t\right]+p_tE_t^R\left[\beta\Lambda_{t,t+1}R^K_{t+1}Q_tS_t^B\right]+D_t\frac{\varphi_t}{\varrho_t}\mu_d\left(\frac{M_t}{D_t}\right)^{\frac{1}{\eta_m}}-D_t \quad (D.4)$$

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

$$\text{err}_5 = \lambda_t - \frac{(1-p_t)E_t^N\Lambda_{t,t+1}R^K_{t+1}[\theta\lambda_{t+1}\Sigma_{t+1}+(1-\theta)](1-\overline{\omega}_{t+1})}{\Sigma_t-(1-p_t)E_t^N[\Lambda_{t,t+1}R^K_{t+1}\overline{\omega}_{t+1}]-p_tE_t^R[\Lambda_{t,t+1}R^K_{t+1}]} \quad (D.6)$$

$$\text{err}_6 = N_t+D_t-Q_tS_{B,t} \quad (D.7)$$

$$\text{err}_7 = 1+\psi_mCa_t-\left(\beta E_t\left[\Lambda_{t,t+1}\Pi^{-1}_{t+1}\right]+\frac{\varphi_t}{\varrho_t}\left(\frac{M_t}{Ca_t}\right)^{\frac{1}{\eta_m}}\right) \quad (D.8)$$

$$\text{err}_8 = 1-\left(\beta E_t\left[\Lambda_{t,t+1}\Pi^{-1}_{t+1}\right]R_{CB,t}+\frac{\varphi_t}{\varrho_t}\mu_{cb}\left(\frac{M_t}{D_{CB,t}}\right)^{\frac{1}{\eta_m}}\right) \quad (D.9)$$

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

$$\text{err}_8 = 1 + \tilde{\psi}_{\bar{D}_{CB}} \max[D_{CB,t} - \bar{D}_{CB}, 0] - \left(\beta E_t \left[\Lambda_{t,t+1} \Pi_{t+1}^{-1} \right] R_{CB,t} + \frac{\varphi_t}{\varrho_t} \mu_{cb} \left(\frac{M_t}{D_{CB,t}} \right)^{\frac{1}{\eta_m}} \right) \tag{D.10}$$

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

$$N_{t+1} = \max \left[R^K_{t+1} Q_t S_{B,t} - \overline{R}_t D_t, 0 \right] + (1-\theta)\zeta S_t. \tag{D.11}$$

A run occurs at a specific point if

$$R^K_{t+1} Q_t S_{B,t} - \overline{R}_t D_t \leq 0. \tag{D.12}$$

In such a future state, the weight of a run is 1. In the other state, the weight of a run 0.[41] 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 cashpolicy function, this could be written as:

$$Ca_{j+1}(\mathbb{X}_t; \Theta^P) = \alpha^{U1} Ca_j(\mathbb{X}_t; \Theta^P) + (1-\alpha^{U1}) Ca_{sol}(\mathbb{X}_t; \Theta^P), \tag{D.13}$$

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

[41] 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.

from step 4:

$$N'_{j+1}(\mathbb{X}_t, \varepsilon_{t+1}; \Theta^P) = \alpha^{U2} N'_j(\mathbb{X}_t, \varepsilon_{t+1}; \Theta^P) + (1 - \alpha^{U2}) N'_{sol}(\mathbb{X}_t, \varepsilon_{t+1}; \Theta^P), \quad \text{(D.14)}$$

$$P_{j+1}(\mathbb{X}_t; \Theta^P) = \alpha^{U3} P_j(\mathbb{X}_t; \Theta^P) + (1 - \alpha^{U3}) P_{sol}(\mathbb{X}_t; \Theta^P). \quad \text{(D.15)}$$

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.

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

Figure E.11 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.

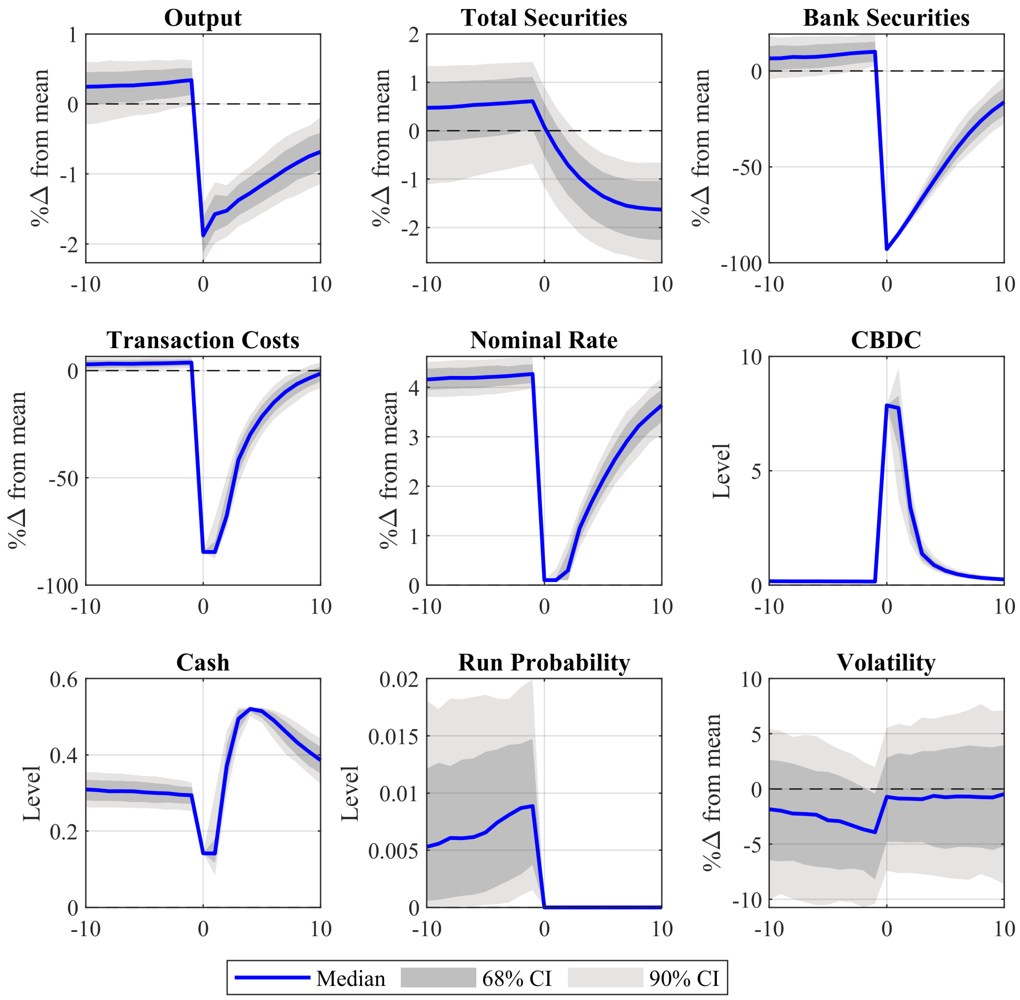

Figure E.11: Event analysis based on a simulation of 100000 periods. It shows the average response across (with the 68% and 90% confidence interval) across all observed runs using an event window (10 periods before and the run). The scales are either percentage deviations from the average ($\%\Delta frommean$), percent (%) or level.

Appendix F. Policy Design: Optimal Limit for Keen Scenario

Figure F.12 shows the impact of a holding limit $\bar{D}_{CB}$ for the scenario. The optimal limit is located at 0.25.

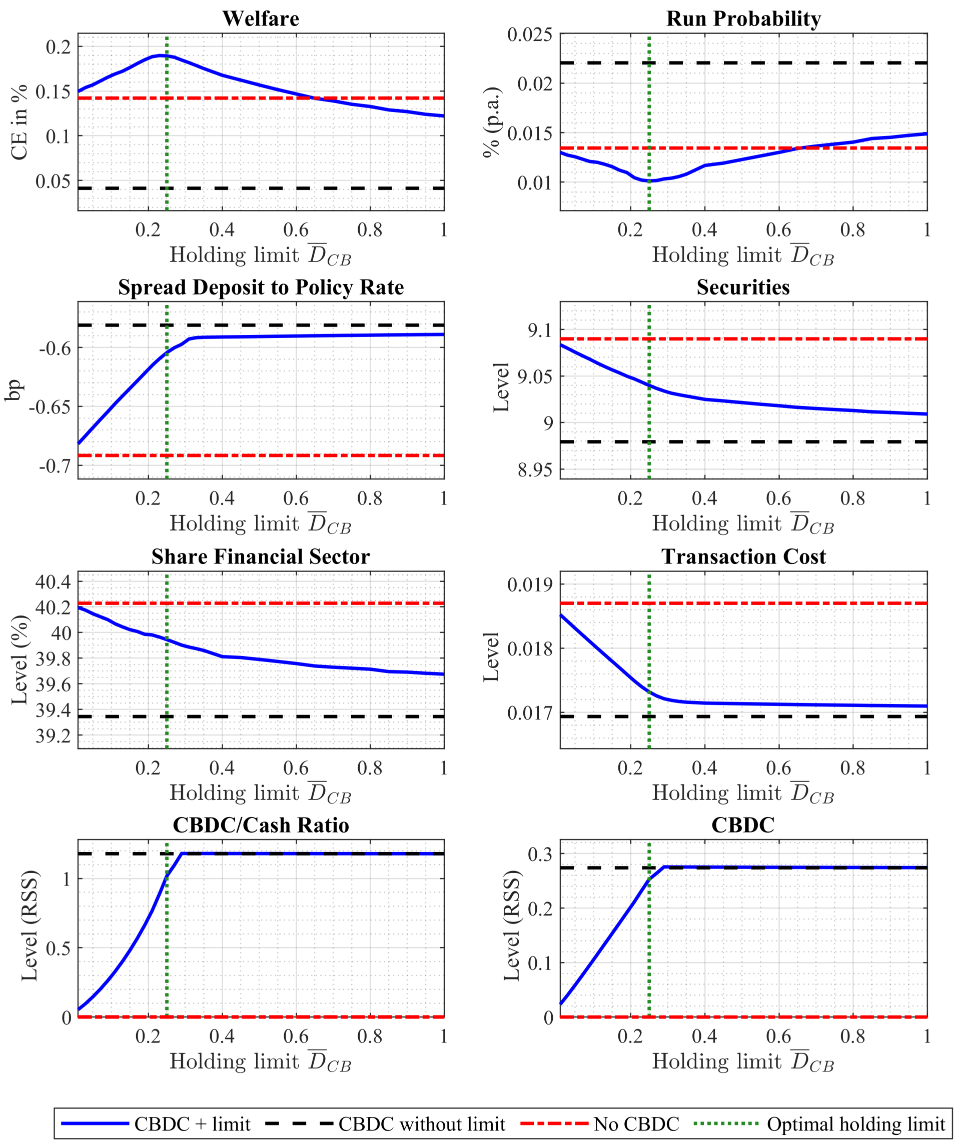

Figure F.12: Impact of holding limits for CBDC $\overline{D}_{CB}$ on the equilibrium (blue line) for the keen scenario $\mu_{cb} = 0.98$. The horizontal lines show CBDC without limit (black dashed) and the economy without CBDC for comparison. Most variables display their mean. CBDC-cash-ratio and CBDC 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).