

CBDC and bank capital regulation^{*}

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Abstract

We show that news about the digital euro moderately increase perceived bank riskiness and optimal capital needs for low capitalized banks. Using a DSGE model calibrated to the euro area that replicates such evidence, we find that setting a limit on individual CBDC holdings can mitigate potential adverse effects on bank riskiness and economic activity. Optimal structural capital requirements enhance the mitigation effect of the holding limit, while optimal cyclical capital regulation contributes to strengthening the stabilization effect of CBDC on output.

Keywords: central bank digital currency, digital euro, bank capital requirements, bank risk, financial frictions.

JEL classification: E42, E44, E58, G21.

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1 Introduction

As the wide majority of central banks worldwide are exploring the implications of issuing a retail central bank digital currency or CBDC (Di Iorio et al. 2024), a burgeoning literature on this topic has emerged in recent years. In the absence of historical experience and data for empirical analysis, the bulk of this literature has so far predominantly been theoretical. While most of the few available empirical studies focus on providing rough estimates for CBDC demand, the majority of the theoretical ones emphasize the risk of bank disintermediation through bank deposit substitution. These are important first steps to better understand what the adoption of CBDC could entail, how it might transmit and affect banks and the macroeconomy, and what is the optimal design of a limit on individual CBDC holdings aimed at calibrating the amount of central bank digital currency in circulation.¹

One next step would be to empirically assess how CBDC is expected to affect banks' resilience and how this could alter optimal banking regulation. The main contribution of this paper is twofold. First, we provide empirical evidence on the impact of digital euro-related news on perceived bank riskiness, bank capitalization and optimal bank capital needs. Second, we develop and utilize a macro-banking model that captures this evidence and provides a rationale for micro and macro-prudential bank capital regulations (by allowing for bank risk failure and binding borrowing constraints for banks and firms) to: (i) inspect the transmission and effects of CBDC on bank riskiness, bank capitalization and optimal bank capital regulation, (ii) study the extent to which a limit on individual CBDC holdings could mitigate (or even neutralize) these effects, and (iii) assess how optimal bank capital regulation impacts the main macroeconomic effects through which CBDC has welfare consequences.

In Section 2, we adopt the same empirical strategy as in Burlon et al. (2024) to provide evidence on the perceived impact of CBDC on bank riskiness and bank capitalization (and on how this can influence the optimal level of capital requirements) by exploiting digital euro announcement effects on bank stock valuations. We find that perceived bank riskiness moderately increases in response to (negative) CBDC news over the first year from the shocks, especially for banks with ex-ante lower capital buffers. Banks react by accumulating capital to absorb the additional layer of bank risk. This applies to all banks but especially to those with ex-ante low capital buffers, as they are subject to a higher repricing of their risk profile and stand to gain most from a reassessment of their optimal capital needs. This response is interpreted as an increase in perceived optimal capital needs.

¹The main advanced economies running a retail CBDC project are considering a limit on individual CBDC holdings as a key design feature aimed at calibrating the amount of CBDC in circulation (see, e.g., the ECB second progress report on the digital euro preparation phase and the Bank of England & HM Treasury Consultation Paper titled *The digital pound: a new form of money for households and businesses?*)

In Section 3, we present the main features of the quantitative macro-banking DSGE model and its calibration to quarterly data of the euro area. We consider a monetary economy populated by two types of agents: households, who are net savers and obtain liquidity services from holding commercial bank money and central bank money (CBDC in this case) - which are imperfect substitutes as in Drechsler et al. (2017) - and; entrepreneurs, who are net borrowers as they discount the future more heavily than households and obtain bank lending against commercial real estate (CRE) collateral (Iacoviello 2005a).² Such CRE is rented by intermediate goods producers, who combine it with labor (through a Cobb-Douglas technology) to produce intermediate goods under monopolistic competition and set prices à la Calvo (1983). Bankers are a special member of households (Gertler and Karadi 2011) and banks intermediate financial resources by borrowing from households and lending to entrepreneurs. In maximizing the net present value of bankers' equity share, banks are subject to a balance sheet identity and a regulatory capital requirement. They face idiosyncratic loan return shocks, which are modeled as in Bernanke et al. (1999) and are the main driver of the idiosyncratic bank default risk in the model. Banks operate under limited liability, with a fraction of deposits being insured by a deposit insurance scheme. They underprice the risk involved in bank loans, which gives a role for micro-prudential capital regulation. The borrowing limits faced by NFCs and banks are binding in a neighborhood of the steady state due to the relative impatience of the former and the low cost of uninsured deposit funding relative to that of bank equity, respectively. This amplifies credit and output fluctuations (Kiyotaki and Moore 1997) and - combined with the underpricing of bank risk failure - provides a rationale for macro-prudential (cyclical) capital regulation.

The model is completed with a policy block. The (macro-)prudential authority sets bank capital requirements according to a simple policy rule that comprises a structural (steady-state) component, γ , and a cyclical one, $\gamma_x \tilde{X}_t$. The CCyB parameter, γ_x , measures the degree of responsiveness of regulatory capital requirements to changes in a macro/financial indicator of the choice of the regulator, $\tilde{X}_t$.³ The central bank sets the (risk-free) policy rate according to a simple Taylor-type rule and issues CBDC by means of a simple quantity rule. The model captures key CBDC design features envisaged in the digital euro project: (i) only households (and not firms) are allowed to have CBDC holdings, (ii) such holdings are not remunerated, and (iii) the amount of CBDC in circulation is calibrated via a (quantity) limit on individual CBDC holdings.

Section 4 distills the main mechanisms through which the issuance of CBDC affects bank riskiness, bank capitalization and the overall economy. Due to the imperfect substitutability between the

²The idea that these monetary instruments provide liquidity services is captured by allowing for money in the utility function (Sidrauski 1967). The substitutability across these means of payment is mainly accounted for by defining liquidity services as a CES aggregator of the three monetary instruments with an elasticity of substitution larger than 1.

³The term CCyB refers to the countercyclical capital buffer envisaged in the Basel III Accords.

two monetary instruments, the issuance of CBDC only partially replaces bank deposits and leads to an expansion of aggregate liquidity services. The bank deposit rate escalates as households' supply of deposit funding recedes, thereby exerting a downward pressure on bank profitability through an increase in the weighted average cost of capital (WACC). In line with the evidence, such an effect on bank profitability only has a marginal impact on bank riskiness (proxied by the bank default probability) - whose magnitude nevertheless depends on bank capitalization - and exerts a downward pressure on bank equity. The banking sector reacts to the jump in the WACC by tightening credit supply. That effect leads to a decline in private consumption and CRE investment, with the latter triggering a fall in property prices. The impact on net output (private consumption) is negative but very moderate, partly due to a fiscal expansion induced by CBDC through two sub-channels. The aggregate economic cost of bank risk failure decreases with CBDC as bank assets (lending) go down. Moreover, taxes levied on households decline as seigniorage revenues soar.⁴

In Section 5, we then use the calibrated model to study optimal structural and cyclical capital requirements. Optimal (i.e., social welfare-maximizing) structural capital requirements are driven by a trade-off. On the one hand, higher regulatory capital ratios improve the capacity of banks to withstand losses, thereby reducing their default probability (and the related aggregate economic cost) and encouraging banks to extend more loans. On the other hand, higher capital requirements can hinder lending supply and real economic activity by exerting an upward pressure on bank funding costs as the share of the costlier financing source (i.e., equity) soars in the funding mix. The issuance of CBDC has heterogeneous implications for welfare-maximizing structural capital requirements across agent types. Given that CBDC moderately lowers private consumption, households find it optimal to have a tightening of capital requirements that contributes to offset such effect by reducing the aggregate economic cost of bank risk failure (proxied by the deadweight loss) and lump-sum taxes. As issuing CBDC negatively impacts bank lending supply, entrepreneurs find it optimal to have a relaxation of capital requirements that compensates for such effect by encouraging banks to extend more loans. Thus, the net impact of CBDC on optimal structural capital requirements will depend on the weight of each agent type in the measure of social welfare.⁵ We find a calibration for the limit on individual CBDC holdings that roughly neutralizes any potential impact of CBDC on bank riskiness and optimal structural capital requirements while still inducing significant welfare gains via liquidity services provision.

Optimal cyclical capital regulation induces significant stabilization and welfare gains through the

⁴The aggregate economic cost of bank risk failure is proxied by making the empirically relevant assumption that a share of the bank assets which default cannot be repossessed by the deposit insurance scheme. This cost can also be interpreted as bank resolution costs and represents a deadweight loss for the economy.

⁵We propose a standard measure of social welfare specified as a weighted average of the expected life-time utility of savers and borrowers.

following mechanism; the (macro-)prudential authority builds the CCyB when the bank lending spread is expected to increase, thereby strengthening bank resilience (proxied by a decline in the bank default probability) when there is more headroom for doing so. As a consequence, the aggregate economic cost of bank risk failure and taxes recede, ultimately fostering private consumption and stabilizing real economic activity with any unintended consequences on short-term bank lending being marginal. There is a certain degree of substitutability between the stabilization capacity of cyclical capital regulation and that of CBDC.⁶ For this reason, the size of optimal cyclical capital requirements and the associated welfare gains decrease with the amount of CBDC in circulation.

Lastly, we assess the impact of optimal bank capital regulation on each of the three main macroeconomic effects that drive the aggregate welfare consequences of CBDC (Burlon et al. 2024). The liquidity services effect that improves households' welfare is roughly unaffected by optimal capital regulation. However, the bank disintermediation effect that is particularly harmful to borrowers is significantly mitigated by raising structural capital requirements to their optimal levels, as it reduces bank riskiness and encourages banks to extend more loans. Moreover, if the amount of CBDC in circulation is calibrated with a holding limit, optimal cyclical capital regulation strengthens the stabilization effect of CBDC as it enables a more pronounced decline in aggregate economic volatility.

Related Literature This paper contributes to the empirical literature on central bank digital currencies. Most of these studies focus on providing a range of estimates for CBDC demand and on identifying the key factors behind such potential demand by exploiting survey data (Huynh et al. 2020; Bijlsma et al. 2021; Abramova et al. 2022; Choi et al. 2023; Bidder et al. 2024; Nocciola and Zamora-Pérez 2024). To the best of our knowledge, Burlon et al. (2024) is the first empirical study that investigates the impact of CBDC on banks. The paper provides evidence on the estimated impact of CBDC news on bank valuations and lending by exploiting information on market reactions to digital euro-related news. Our paper complements such analysis with a more comprehensive dataset by providing a wealth of new evidence on the estimated impact of digital euro news on perceived bank riskiness, bank capitalization and market perceptions about a possible shift in bank optimal capital needs.

Our work connects with the rapidly growing literature on the implications of CBDC for the banking sector and the macroeconomy (e.g., Keister and Sanches 2022; Chiu et al. 2021; Agur et al. 2021; Barrdear and Kumhof 2022; Ferrari Minesso et al. 2022; Bacchetta and Perazzi 2021; Piazzesi and Schneider 2022; Assenmacher et al. 2023; Kumhof et al. 2023). In general, these set-ups

⁶For details on the mechanisms through which the issuance of CBDC generates a stabilization effect, see Burlon et al. (2024).

model at least one financial friction or market imperfection in the financial sector. Among others, monopolistic competition in the banking sector (e.g., [Andolfatto 2021](#); [Chiu et al. 2019](#); [Paul et al. 2024](#)), central bank collateral requirements (e.g., [Assenmacher et al. 2021](#); [Williamson 2022](#); [Burlon et al. 2024](#)), a frictional interbank market ([Abad et al. 2022](#)) or asymmetric information ([Muñoz and Soons 2023](#)). The wide majority of these set-ups are macroeconomic models that do not allow for bank risk failure. The exception is, perhaps, [Bidder et al. \(2024\)](#), who build a macroeconomic model with endogenous bank runs à la [Gertler et al. \(2020\)](#) to study the impact of CBDC on bank intermediation in normal times and during bank run episodes. Also related to our work, [Whited et al. \(2022\)](#) estimate the effects of CBDC on banks through the lens of a dynamic banking model that allows for bank default and captures the mechanisms of interest rate risk (stemming from maturity transformation) and capital requirements through which CBDC can affect these financial intermediaries. In our model, bank default is fundamentally driven by idiosyncratic asset return shocks à la [Bernanke et al. \(1999\)](#) and is independent from the performance of individual loans. For tractability, this is the assumption typically made in the macro-banking literature on bank capital regulation to account for bank risk failure (e.g., [Mendicino et al. 2020, 2024](#); [Elenev et al. 2021](#)). The empirically relevant assumptions of lending risk underpricing and binding borrowing limits in the financial and the non-financial sectors of the economy provide a strong rationale for micro and macro-prudential capital regulations, respectively, and give rise to optimal structural and cyclical capital requirements. This allows us to inspect the channels through which CBDC affects bank riskiness, bank capitalization and optimal capital requirements.

There are several papers in the CBDC literature that incorporate one or more of several regulatory frictions that can alter the allocative and macroeconomic consequences of CBDC. Namely the central bank collateral framework, bank capital regulation and liquidity requirements (e.g., [Meller and Soons 2022](#); [Williamson 2022](#); [Burlon et al. 2024](#)). However, none of them study the actual impact of CBDC on the optimal design and calibration of these regulations. Ours is, perhaps, the first contribution on the effects of CBDC on optimal banking regulation (with a focus, in this case, on bank prudential capital requirements) and the calibration of the hypothetical CBDC holding limit that would be required to mitigate (or even neutralize) such effects.

Lastly, this paper builds on the literature on quantitative macroeconomic models of bank capital regulation (e.g., [Van den Heuvel 2008](#); [Angeloni and Faia 2013](#); [Abad 2019](#); [Aguilar et al. 2019](#); [Begenau 2020](#); [Malherbe 2020](#); [Muñoz 2021](#); [Begenau and Landvoigt 2022](#)). Many of the macroeconomic models that offer a convincing rationale for prudential bank capital regulation by allowing for bank risk failure focus on the role and justification for structural (steady-state) bank prudential capital requirements, giving little to no room for welfare-improving cyclical capital regulation (e.g., [Mendicino et al. 2018, 2020, 2024](#); [Canzoneri et al. 2021](#); [Abad et al. 2024](#)).⁷ This

⁷We show that without the need of assuming additional layers of default typically considered in this strand of

result is generally influenced by the assumption of endogenous leverage ratios in the real sector of the economy. We depart from this assumption and allow for binding borrowing limits also in the NFC (entrepreneurs) sector. This assumption - combined with that of binding bank capital requirements - amplifies financial and economic fluctuations and gives a prominent role for cyclical bank capital regulation.⁸

Most of the macroeconomic models that assume any sort of bank risk or bank panics and find a prominent role for cyclical bank capital regulation are those that study the benefits of releasing the CCyB when the economy switches to the bad state of nature (i.e., in extraordinary crisis times). Among others, [Corbae and D’Erasmus \(2021\)](#), [Elenev et al. \(2021\)](#), and [Faria-e-Castro \(2021\)](#).⁹ In contrast, ours focuses on the stabilization and welfare gains of building and adjusting the CCyB over the cycle (i.e., outside extraordinary crisis times). This permits us to assess the interactions between the over-the-cycle stabilization capacity of cyclical bank capital regulation and that of CBDC ([Burlon et al. 2024](#)).

The paper is organized as follows. Section 2 presents novel empirical evidence on the estimated impact of digital euro news on perceived bank riskiness and bank capitalization. Section 3 describes the key features of the macro-banking DSGE model and its calibration to quarterly data of the euro area. Section 4 distills the transmission mechanisms of CBDC and illustrates how the model captures our empirical evidence. Section 5 studies the interactions between CBDC and optimal bank capital regulation. Section 6 concludes.

2 Empirical Evidence

In this section we provide empirical evidence on the perceived impact of CBDC on bank capitalization and bank riskiness, and how this can have a bearing on the optimal level of capital requirements. We follow closely [Burlon et al. \(2024\)](#) and exploit digital euro announcement effects on bank stock valuations. These investors’ views allow us to measure the potential impact of CBDC adoption and institutional features on bank funding, liquidity, and ultimately profitability.

the literature (corporate and/or household default risk) other than bank default risk, this stylized model matches the same key bank data targets, captures the same transmission mechanisms and trade-offs, yields similar capital requirement-induced individual and social welfare effects (e.g., [Mendicino et al. 2018](#)) and related optimal structural capital requirements ([Mendicino et al. 2020](#)).

⁸The assumption of binding borrowing constraints faced by firms is empirically relevant. At the aggregate level the NFC sector is credit constrained ([Banerjee and Duflo 2014](#)), firms that are credit constrained are found across the entire firm-size distribution ([Ferreira et al. 2023](#)), and such financial constraints have large real effects ([Campello et al. 2010](#)).

⁹One of the few exceptions is, perhaps, [Davydiuk \(2017\)](#), who finds that it is optimal to adjust capital requirements over the cycle between 5% and 7% by responding to changes in GDP, the credit gap and asset prices. In contrast, we find that optimal capital requirements are higher on average and optimally adjust over the cycle in response to expected shifts in the bank lending spread ([Muñoz and Smets 2024](#)).

We then trace these impacts on banks’ capital adequacy and creditworthiness, showing that the perceived challenges to banks’ internal capital generation capacity can alter the optimal capitalization levels chosen by banks.

2.1 Stock Market Reactions to Digital Euro News Over Time

Following closely [Burlon et al. \(2024\)](#), we estimate banks’ abnormal returns associated with digital euro news using a [Fama and French \(1993\)](#) three-factor model.¹⁰ We fit the model to stock market returns of euro area banks, and we classify returns as abnormal to the extent that they deviate from the returns explained by the Fama-French factors. We retrieve data on bank stock market returns and CDS spreads at the daily frequency from [Refinitiv Eikon \(2022\)](#). Our sample consists of 681,012 daily observations on 221 banks resident in 18 euro area countries from 16 January 2003 to 8 May 2024.¹¹ For each bank, we estimate the following model:

$$R_{b,t} = \alpha_b + \beta_{m,b}R_{m,t} + \beta_{HML,b}R_{HML,t} + \beta_{SMB,b}R_{SMB,t} + \sum_{e=1}^E \gamma_b^e D_t^e + \varepsilon_{b,t}, \quad (1)$$

where $R_{b,t}$ is the return on the stock of bank b between the day before and the day after t , $R_{m,t}$, $R_{HML,t}$ and $R_{SMB,t}$ are the excess return on the market portfolio, the value versus growth factor (i.e., the return on a portfolio long high market-to-book firms and short low market-to-book firms), and the size factor (i.e., the return on a portfolio long small firms and short large firms), respectively. The abnormal daily returns are computed by using the estimated coefficients γ_b^e of the dummy variables D_t^e for each event $e = 1, \dots, E$, which take value 1 if the event e takes place in day t .

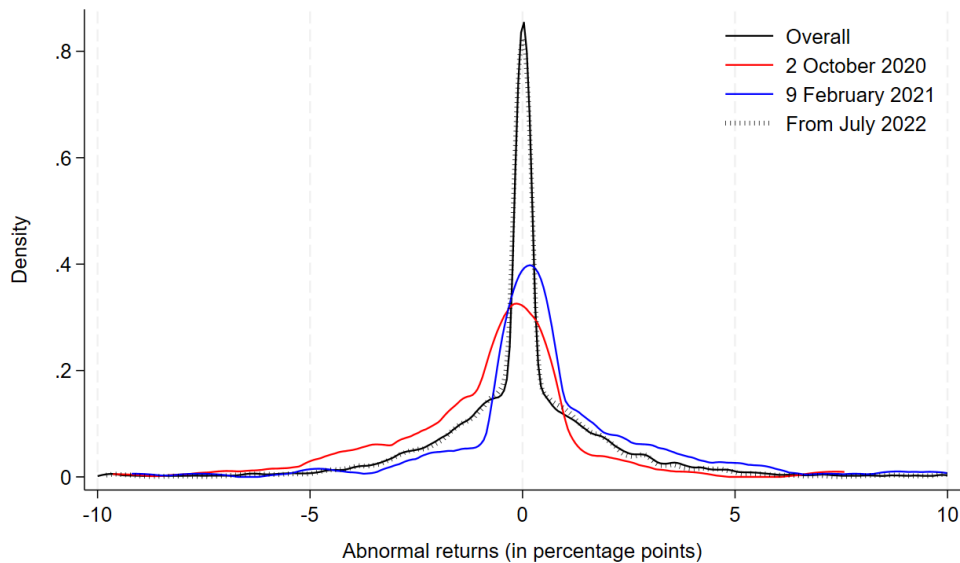
Table [A.1](#) reports the full list of events related to digital euro considered in the analysis. All these events have a precise date of publication, which is used as date to identify the event. The series includes 88 events distributed from January 2020 to May 2024, increasing the sample originally covered in [Burlon et al. \(2024\)](#) with three years worth of data, targeted communication and progress reports around the digital euro project. Events relate to public interventions by ECB board members, ranging from official press releases to interviews and speeches, to entries in ECB’s official blog and other outlets, but include also sourced stories and leaks about the project which were reported in Bloomberg News and are thus likely to have generated a market impact. We report the distribution of abnormal stock market returns around these events across individual banks in Figure [1](#). Two key early events, already explored in [Burlon et al. \(2024\)](#), were the announcement

¹⁰See [Sefcik and Thompson \(1986\)](#), [MacKinlay \(1997\)](#) and [Binder \(1998\)](#) for insights on the use of event studies in empirical finance.

¹¹Euro area countries represented in the analysis include Austria, Belgium, Cyprus, Germany, Estonia, Spain, Finland, France, Greece, Croatia, Ireland, Italy, Luxembourg, Malta, The Netherlands, Portugal, Slovenia and Slovakia.

of the Report on the Digital Euro on 2 October 2020 –with the ensuing negative stock reactions for banks dependent on deposit funding– and the explicit mention of holding limits on 9 February 2021 –with an opposite, positive response of bank stocks–. At the same time, there were several other announcements related to the digital euro that provided market participants over the years, with additional details on the viability, design, progress and reception of the digital euro project. Markets’ reactions to these events were on average moderate but presented also large variation across banks, driven by the latter’s exposure to the evolving landscape surrounding the future potential adoption of a CBDC in the euro area.

Figure 1: Abnormal stock returns of euro area banks around Digital euro events



Notes: The figure reports the Kernel density of the distribution of abnormal stock market returns $\hat{\gamma}_b^e$ obtained estimating the 3-factor Fama-French model reported in (1). Abnormal returns are computed for each bank b and for each the digital euro event e reported in Table A.1, and are measured in percentage points. The solid black line is the density for the pooled sample. The red and blue lines report the density for the cross-sectional distribution across banks of the abnormal returns measured on 2 October 2020 and 9 February 2021, respectively. The dotted black line is the density for the distribution across events and banks in the pooled subsample of events from 1 July 2022 to the end of the sample.

Our large sample of events allows the analysis not to be crucially dependent on specific events and outliers, or isolated confounding factors like the coincidence with other announcements. As a consequence, the distribution of the identified abnormal returns to bank stocks is similar over time, despite the prominence of some key events. For example, Figure 1 shows that the distribution of abnormal returns after the start of the hiking cycle in July 2022 did not differ from before. While our large sample makes our results robust to the inclusion of isolated, key events unrelated to the digital euro project that generated market reactions concomitant with digital euro events, in Figure A.1 we report three key events that we have dropped from our sample due to their clear coincidence with other potential drivers. Two events coincide with monetary policy announcements. While

Table 1: Summary statistics in regression sample

Variable	Unit	Description	Obs.	Mean	St.Dev.
Negative CBDC shock	p.p.	Inverse of abnormal stock returns around digital euro events cumulated from 1 January 2020 to day t for bank b .	1,106	-3.24	8.91
Change in CDS spread	b.p.	Change in Credit Default Swap spread of bank b from day t to day $t+360$.	32,080	-10.09	98.55
Change in capitalisation	p.p.	Change in CET1 ratio of bank b from quarter q to quarter $q+8$.	1,106	0.44	1.95
Change in capital guidance	p.p.	Change in P2G guidance of bank b from quarter q to quarter $q+8$.	1,106	0.38	2.08
Change in capital buffers	p.p.	Change in difference between CET1 ratio and P2G guidance of bank b from quarter q to quarter $q+8$.	1,106	0.06	2.70
CDS spread	b.p.	Credit Default Swap spread of bank b in quarter $q-1$.	1,106	133.43	238.58
Capital buffer	p.p.	Difference between CET1 ratio and P2G guidance of bank b in quarter $q-1$.	1,106	4.46	3.45
ROA	p.p.	Return on assets for bank b in quarter $q-1$.	1,106	0.49	0.84
Assets	log	Main assets for bank b in quarter $q-1$, in logs of €million.	1,106	11.50	1.43
NPL ratio	p.p.	Ratio of non-performing loans over gross carrying amounts for bank b in quarter $q-1$.	1,106	7.41	8.07
Deposit ratio	p.p.	Ratio of deposits from the non-financial private sector over main liabilities of bank b in quarter $q-1$.	1,106	39.35	20.37
Liquidity net of TLTROs	p.p.	Ratio of the difference between central bank reserves in excess of MRR and outstanding TLTROs over main assets of bank b in quarter $q-1$.	1,106	1.67	5.84
Securities holdings	p.p.	Ratio of securities holdings over main assets of bank b in quarter $q-1$.	1,106	8.51	5.61

Notes: The table reports summary statistics for the main variables used in the empirical analysis. Each observation is a bank in a given quarter, except for changes in CDS spreads which are reported at daily frequency. The final regression sample consists of 43 banks followed for 29 quarters from 2015Q1 to 2022Q1, with the 8-quarters-ahead horizon reaching until 2024Q1.

these tended by design to be located in windows of time that showed little to no overlap with monetary policy meetings, in our sample there were two days (10 September 2020 and 15 June 2023) when a digital euro event (a speech by ECB President Lagarde and the leak regarding a EU Commission report on digital euro design) coincided with a monetary policy announcement (the monetary policy decision taken by the Governing Council of the ECB on the same day). Both events were associated with minor abnormal bank stock returns. The third excluded event was on 10 March 2023 (a speech by ECB Board Member Panetta) and coincided with the sharp repricing of bank stocks in occasion of the Silicon Valley Bank and Credit Suisse collapses.

2.2 Data for regression analysis

Our empirical analysis relies on various confidential data sources. Table 1 summarises the rich set of bank characteristics in the main regression samples employed in the analysis.

First, on top of the data on bank stock market returns mentioned above, we retrieve data on CDS spreads at the daily frequency from [Refinitiv Eikon \(2022\)](#), so we can compute how much markets' assessment of banks' creditworthiness has changed at each point in time and for each horizon.

Second, we exploit confidential information on bank-specific capital requirements and actual capitalisation levels coming from the Supervisory Review and Evaluation Process (SREP) put in place by the Single Supervisory Mechanism (SSM). Crucially, we can incorporate in the analysis the distinction between different types of capital requirements, from the Pillar 2 requirements which

define the threshold of CET1 capital below which restrictions on dividend distributions are activated (the so-called Minimum Distributable Amount, or MDA, trigger) to Pillar 2 Guidance that instead incorporate also bank-specific ad-hoc guidance by the supervisory authorities on the preferable level of capital for each bank dependent on banks' business model, balance sheet structure, risk profiles (including credit risk and interest rate risk, but also operational risk and governance structure for example), among other characteristics. The gap between capital levels and capital requirements provides us with banks' management buffers, that is, the amount of capital that banks are in higher liberty to deploy towards business applications or distribute to shareholders. Variation in these variables is quarterly, coincident with the publication of supervisory statistical information. Merging these data with listed banks' stock returns and CDS spreads leaves us with 43 banks followed from 2015Q1 to 2024Q1. This allows us to explore how capitalisation changes at different horizons.

Third, we complement these data with bank-level information on balance sheet structures from the individual Balance Sheet Items (iBSI) dataset. This is a proprietary database maintained by the ECB, which reports the main asset and liability items of over 300 banks resident in the euro area at a monthly frequency. Moreover, we gather direct information on central bank borrowing under the targeted longer-term refinancing operations (TLTROs) and levels of central bank reserve holdings in excess of the minimum reserve requirements (MRR) at the reserve maintenance period frequency (roughly 6 weeks) from the confidential reporting obligations that banks have in order to be counterparts of the Eurosystem. Finally, we further augment our database with data on banks' profitability and NPL ratios sourced from bank financial statements maintained by Bureau van Dijk's Orbis BankFocus.

2.3 Impact of CBDC shocks on perceptions of bank riskiness

In what follows we study whether and to which extent exposure to CBDC news has an impact on banks' CDS spreads. To allow for dynamic impacts that unfold over time, we estimate impulse response functions for individual banks' CDS spreads to changes in the cumulated abnormal returns associated with digital euro related events. We do so using local projection models ([Jordà 2005](#); [Ramey 2016](#)).

The specification is as follows:

$$\Delta^h \text{CDS spread}_{b,t} = \xi^h \hat{\Gamma}_{b,t} + \delta^h X_{b,t-1} + \alpha_b^h + \alpha_t^h + \varepsilon_{b,t}^h, \quad (2)$$

where $\Delta^h \text{CDS spread}_{b,t}$ is the change in bank b 's CDS spread between day t and day $t + h$, with h between 1 year before and 2 years after day t . $\hat{\Gamma}_{b,t}$ is our treatment variable defined as the (cumulated) abnormal returns in day t , $X_{b,t}$ are time-varying bank controls, α_b^h are bank fixed

effects and α_t^h are day fixed effects. $\varepsilon_{b,t}^h$ are the standard errors. Bank controls $X_{b,t}$ include the (lagged value of) the CDS spread itself, the capital buffer above the P2G guidance, profitability, size in terms of assets, NPL ratio, deposit ratio, central bank liquidity holdings in excess MRR and net of TLTROs, and securities holdings. We cluster errors at the bank-quarter level.

The main challenge to identification is to make sure that pre-existing characteristics of banks potentially associated with the response of stock market returns to CBDC news do not determine the future change in banks' CDS spreads in concomitance with CBDC news themselves. Our empirical specification is geared to ensure robustness to this challenge for several reasons.

First, we rely on banks' high-frequency stock returns around news related to the digital euro, which plausibly rules out reverse causality and endogeneity problems associated, among other issues, to the influence of banks' pre-existing characteristics. In general, the level of stock valuations may be related to bank characteristics that can also alter the reactivity of CDS spreads to shocks. For instance, a higher profitability or a lower NPL ratio make banks more valuable in the eyes of potential risk-sensitive investors and, at the same time, they can also change the premia that fixed-income investors ask in response to shocks. By focusing on changes in stock valuations around key events, we avoid this issue.

Second, by focusing on abnormal returns as identified by a Fama-French 3-factor model, we filter out from the measurement of CBDC news other simultaneous determinants of stock returns that may be blurring the responsiveness of markets to our shocks. These alternative determinants include macroeconomic news and developments, policy announcements, changes in the regulatory and market structure framework, bank business models, among others.

Third, the inclusion of a large battery of time-varying bank controls reduces the role of confounding factors and additional channels of transmission of shocks occurring in parallel to CBDC news. The level of the CDS spread controls for markets' assessment of a given bank creditworthiness. The level of capitalisation net of capital requirements and the guidance provided during the supervisory process controls for the capital leeway that the bank has to redeploy to profitable business initiatives or to distribute to shareholders, which ultimately pins down also its cost of equity. The level of profitability in the form of a bank's return of assets measures its internal capital generation capacity and its medium-to-longer term ability to maintain its creditworthiness in response to shocks. A bank size in terms of main assets is a proxy for several aspects, from a bank's systemic relevance which prompts also a different level of scrutiny from prudential authorities and markets alike, to its exposure to macroeconomic shocks, to its ability to withstand idiosyncratic manifestations of credit, interest and operational risks from its larger pool of borrowers and investments, among others. The deposit ratio aims to control for the main determinant of stock market responses to CBDC news (Burlon et al. (2024)) but also to reduce the dependence of the identified coefficients

on a bank’s liability structure and business model, especially during a period when developments in aggregate deposits were particularly dynamic. The holdings of central bank liquidity in excess of minimum requirements, especially if in deviations of outstanding TLTROs which were the main form of central bank borrowing in our sample, measures a bank’s net exposure to Eurosystem operations, be it in terms of its business model and location in the distribution of liquidity within the euro area banking system or in terms of its reliance on central bank borrowing in the past and especially as a legacy of the exposure and policy response to the pandemic. The holdings of securities allow us to control for the direct exposure of banks to the quantitative tightening measures adopted especially after the monetary policy pivot between end-2021 and mid-2022, for the unrealised losses that underpinned the vulnerabilities emerged during the March 2023 market turmoil, and for the position in which a bank enters the changes in the Operational Framework of euro area monetary policy announced in the first half of 2024, among others.

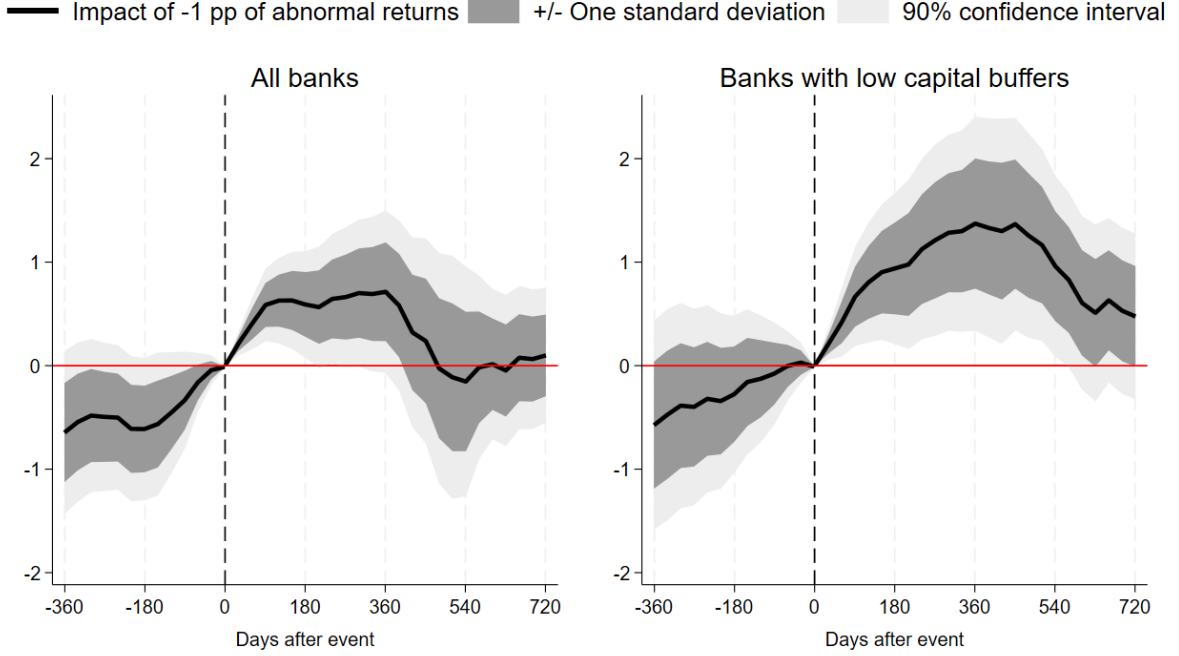
Fourth, the residual unobserved heterogeneity in responsiveness of banks’ CDS spreads to CBDC news is mopped up by bank fixed effects and date fixed effects. The first filter out time-invariant bank characteristics like banks’ business model, market power, specialisation and even exposure to the pandemic or to the energy shock. The second control for the impact of major macroeconomic shocks like the pandemic, the Russian invasion of Ukraine and the subsequent energy shock and fiscal policy response, as well as the start and development of the monetary policy tightening cycle.

Fifth, the clustering of errors at the bank-quarter level controls for spurious autocorrelation within windows with constant values of supervisory variables which are key in our analysis and set of controls.

Figure 2 reports the results of the estimation of model (2). Banks’ riskiness as perceived by markets increases in response to negative CBDC news over the first year from the shocks, especially for banks with ex-ante lower capital buffers. The estimates are economically significant, as one standard deviation of lower stock returns around digital euro events is associated with around 10 basis points of additional CDS spread after one year, which amounts to around one tenth of a standard deviation of the dependent variable despite the wide range of controls and fixed effects included in the specification. The increase is not preceded by significant changes in CDS spreads before the shocks, reinforcing the interpretation that the coefficients indeed reflect the identified impact of CBDC news and not pre-existing trends in CDS spreads spuriously correlated with abnormal returns around digital euro events.

Importantly, the impact of CBDC news is reabsorbed at longer horizon, suggesting that banks’ reactions to the deterioration in market perceptions of their risk profile may be effective in counterbalancing the expected deterioration in bank fundamentals. For instance, [Burlon et al. \(2024\)](#)

Figure 2: **Impact of negative CBDC shocks on CDS spreads**



Notes: The figure reports the estimated coefficients $\hat{\xi}^h$ for each horizon h in the estimation of model (2). The horizon h of each estimate coefficient is reported on the horizontal axis, the magnitude of the estimated coefficient and the related standard deviations and confidence intervals for each horizon are reported on the vertical axis. Banks with low capital buffers are those banks that on average during 2019 had a level of their CET1 ratio net of capital requirements and guidance below the median over the sample period (2.8 percentage points in our sample).

show that, in response to the early announcement of the digital euro project in October 2020 and the negative market reassessment for bank profitability that followed, banks have decreased their loan supply, effectively reducing their risk taking. This would de facto correspond to a decrease in risk-weighted assets via de-risking and deleveraging pressures, which would lead to a higher level of capitalization for an affected bank.

2.4 Impact of CBDC shocks on banks' optimal choice of capital

The optimal level of capital chosen by banks in response to CBDC news is thus crucial to explain how banks' riskiness evolves after negative CBDC-related repercussions reach the market domain. We therefore estimate a model similar to model (2) but aimed at explaining the behavior of capital. The specification is as follows:

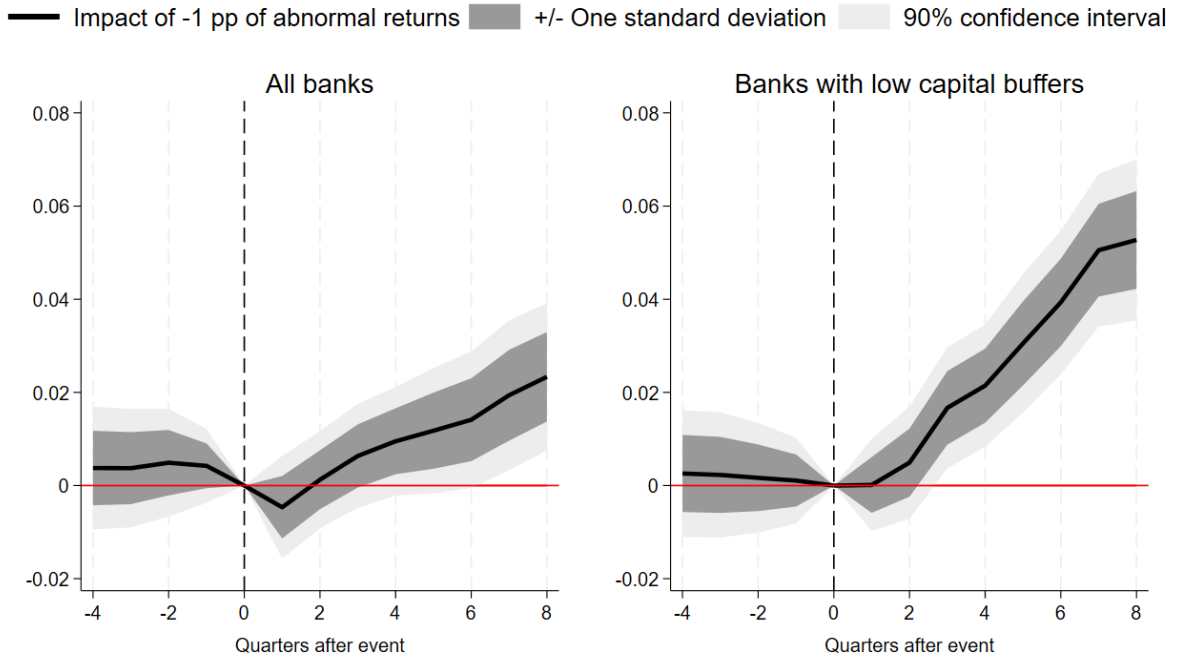
$$\Delta^h \text{Capitalization}_{b,q} = \zeta^h \hat{\Gamma}_{b,q} + \delta^h X_{b,q-1} + \alpha_b^h + \alpha_q^h + \varepsilon_{b,q}^h, \quad (3)$$

where $\Delta^h \text{Capitalization}_{b,q}$ is the change in bank b 's capital between quarter q and quarter $q + h$, with h between 1 year before and 2 years after quarter q . $\hat{\Gamma}_{b,q}$ is our treatment variable defined as

the (cumulated) abnormal returns in quarter q , $X_{b,q}$ are time-varying bank controls, α_b^h are bank fixed effects and α_q^h are quarter fixed effects. $\varepsilon_{b,q}^h$ are the standard errors. $X_{b,q}$ include the same set of bank controls covered in model (2), just at a quarterly frequency. We cluster errors at the bank-quarter level.

Figure 3 shows that indeed the behavior of capital is consistent with an active accumulation of capital reabsorbing the additional layer of bank risk that markets perceived in the immediate aftermath of CBDC news. Capital starts to be accumulated after the impact on CDS spreads reaches its peak, around one year after the events, and reaches significant levels after two years from the events when the impact on CDS spreads is fully compensated. This is true for all banks but particularly large for banks with low capital buffers ex-ante, which are subject to a higher repricing of their risk profile and stand to gain most from a reassessment of their optimal capital needs.

Figure 3: **Impact of negative CBDC shocks on capitalization**



Notes: The figure reports the estimated coefficients $\hat{\zeta}^h$ for each horizon h in the estimation of model (3). The horizon h of each estimate coefficient is reported on the horizontal axis, the magnitude of the estimated coefficient and the related standard deviations and confidence intervals for each horizon are reported on the vertical axis. Banks with low capital buffers are those banks that on average during 2019 had a level of their CET1 ratio net of capital requirements and guidance below the median over the sample period (2.8 percentage points in our sample).

The impact on capital is economically significant. Table 2 illustrates the robustness of the key estimated coefficient to the incremental inclusion of controls to the specification, showing that the estimates consistently hover around 20 basis points of additional capital 2 years after the negative CBDC shocks for each standard deviation of the latter. This increase corresponds to

around 10% of the variation in the dependent variable, and half of the average increase in bank capital over the same horizon in our sample. Column (1) shows that results do not differ even in absence of all the controls and of bank fixed effects, with only the time fixed effects to provide the minimal setting to isolate the impact of cross-sectional differences in the reaction to CBDC news. The inclusion of bank fixed effects and the key bank characteristics in our evidence, i.e. banks' riskiness and capitalisation, already determines the size of the key coefficient reported in our benchmark specification in Column (6). Including also banks' profitability, which presents an additional source of future capital leeway via retained earnings, does not change the size of the coefficient associated with CBDC shocks. Bank assets do explain part of the variation in bank capital, but broadly independently of the variation captured by our key regressor. The same applies to a measure of credit risk like the NPL ratio, or balance sheet characteristics related to the structure of liabilities and assets like the deposit ratio, the liquidity net of TLTROs and securities holdings.

Table 2: **Robustness of the impact of CBDC shocks on bank capitalization**

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	Change in capitalisation 2 years ahead					
Negative CBDC shock	0.014* (0.008)	0.025** (0.010)	0.026** (0.010)	0.024** (0.010)	0.027*** (0.010)	0.023** (0.010)
CDS spread		0.001** (0.000)	0.001** (0.000)	0.001 (0.000)	0.001* (0.000)	0.001** (0.000)
Capital buffer		-0.340*** (0.034)	-0.337*** (0.035)	-0.330*** (0.034)	-0.332*** (0.034)	-0.319*** (0.034)
ROA			0.063 (0.137)	0.060 (0.140)	0.089 (0.138)	0.065 (0.140)
Assets				2.254*** (0.646)	2.697*** (0.596)	2.945*** (0.606)
NPL ratio					-0.037** (0.019)	-0.048** (0.020)
Deposit ratio						-0.019* (0.011)
Liquidity net of TLTROs						-0.092*** (0.017)
Securities holdings						0.010 (0.025)
Bank fixed effects	No	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,106	1,106	1,106	1,106	1,106	1,106
R-squared	0.042	0.297	0.297	0.312	0.316	0.341

Notes: The table reports the estimated coefficients $\hat{\zeta}^8$ for the horizon $h = 8$ in the estimation of model (3). Banks with low capital buffers are those banks that on average during 2019 had a level of their CET1 ratio net of capital requirements and guidance below the median over the sample period (2.8 percentage points in our sample). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 3 shows that the mechanism through which CBDC shocks prompt a higher optimal choice of bank capital is consistent with both a higher benchmark level of capital advised by supervisory

authorities but also via a spontaneous accumulation of capital buffers. Columns (1) and (2) report that the impact on capitalization is particularly pronounced for banks with lower ex-ante capital buffers, consistent with the higher needs for recapitalization captured by the reaction of CDS spreads in Figure 2. Low capital buffer banks have more than twice the reactivity of the average bank, with each standard deviation of CBDC shocks associated with an increase of capitalization two years ahead of almost 50 basis points. In Columns (3) to (6) we change the dependent variable of model (3) while keeping all the rest of the specification constant. Columns (3) and (4) show that also the guidance towards a level of bank capitalization that is considered as adequate during the SREP process by the European SSM reacts to the perceived strains to bank funding, profitability and overall sustainability of the business model captured by the reaction to CBDC news. The increased capital targets are likely to be closer to the standards expected by markets for the specific business model and circumstances of each bank, and hence also closer to the actual capital targets that the bank itself sets for itself. A high role of this guidance would imply that what is considered an optimal response of bank capital to its changing fundamentals is reflected onto actual capital. Consistent with this interpretation, changes in capital guidance induced by CBDC shocks explain 70% of the changes in capitalization induced by the same shocks on the average bank. Interestingly, this is not different between the average bank and banks with lower capital buffers, as the new perceived challenges introduced by the potential adoption of a CBDC in the euro area may be relatively independent from the bank characteristics that determined the lower capitalization of certain banks relative to others in the system. As a result of the close interaction between guidance and actual capitalization, the buffers that banks maintain above their capital guidance do not change in response to CBDC shocks on average, as shown in Column (5). However, Column (6) shows that banks with lower capital buffers adapt their capitalization even more aggressively than the average bank, possibly responding to the market pressures on their perceived riskiness more than what prudential authorities internalize in their guidance to banks.¹²

3 The Model

Consider a monetary, closed, decentralized and time-discrete economy populated by savers and borrowers. Savers are households that provide consumption insurance to two types of members: workers and bankers. Workers supply labor and return their wage income to the household. Bankers devote their net worth to provide equity financing to the banks they manage and transfer their accumulated earnings back to the household. Borrowers are entrepreneurs - also referred to as non-financial corporations (NFCs) - who demand commercial real estate (CRE) and pledge it as

¹²Appendix A provides additional evidence on the reaction of bank capital to CBDC shocks has changed after the start of the tightening period and the related change in interest rate and liquidity environment.

Table 3: **Transmission mechanism of CBDC shocks via capital guidance and buffers**

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	Change in capitalisation		Change in capital guidance		Change in capital buffers	
Sample:	All banks	Low capital banks	All banks	Low capital banks	All banks	Low capital banks
Negative CBDC shock	0.023** (0.010)	0.053*** (0.010)	0.014* (0.008)	0.013* (0.008)	0.009 (0.013)	0.042*** (0.012)
Bank controls	Yes	Yes	Yes	Yes	Yes	Yes
Bank fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,106	640	1,106	640	1,106	640
R-squared	0.341	0.357	0.425	0.499	0.499	0.548

Notes: The table reports the estimated coefficients $\hat{\zeta}^8$ for the horizon $h = 8$ in the estimation of model (3), where we change the sample of reference and the dependent variable as described in each column. Banks with low capital buffers are those banks that on average during 2019 had a level of their CET1 ratio net of capital requirements and guidance below the median over the sample period (2.8 percentage points in our sample). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

collateral to obtain bank lending. This commercial real estate is rented as an input by intermediate goods producers, who combine it with labor to generate intermediate goods under monopolistic competition and by setting prices a la [Calvo \(1983\)](#).

Entrepreneurs discount the future more heavily than households (i.e., $\beta_e < \beta_h$) which effectively implies that, in the aggregate, the former are net borrowers and the latter are net savers. This key assumption ensures that the borrowing constraint faced by entrepreneurs is binding in a neighborhood of the steady state ([Iacoviello 2005b](#)).

Banks finance their loans to NFCs with equity from bankers and deposits held by households, and have to comply with a regulatory capital requirement. Banks operate under limited liability and default when the value of their assets falls below that of their debt obligations. A fraction κ of these bank deposits is insured by a deposit insurance scheme, which is funded with lump-sum taxes. The remaining deposits are uninsured and depositors price them based on the expected potential losses associated with the risk of failure of an average bank. Hence, deposit valuation does not depend on leverage and risk taking choices of each bank, which are assumed to be unobservable to small and dispersed depositors ([Dewatripont et al. 1994](#)). This friction implies that the risk of bank default is not priced at the margin and banks have incentives to lever up excessively (i.e., the capital adequacy constraint is binding) and to underprice the risk involved in lending to NFCs ([Mendicino et al. 2020](#)).

The presence of these two frictions (lending risk underpricing and binding borrowing limits in the financial and the NFC sectors) provides a strong rationale for both structural and cyclical bank capital regulations. The prudential authority sets these structural (steady state) and cyclical capital requirements according to a simple rule.

The monetary authority sets the interest rate on the risk-free asset according to a simple Taylor-type rule. It also issues CBDC according to a simple quantity rule. The model captures key CBDC design features envisaged in the digital euro project: (i) only households (and not firms) are allowed to have CBDC holdings, (ii) such holdings are not remunerated, and (iii) the amount of CBDC in circulation is calibrated via a limit on individual CBDC holdings.

The next subsection describes the main features of the model in greater detail. The full list of equilibrium conditions of the model is available in Appendix B.

3.1 Main Features

3.1.1 Households: Savers

Let $c_{h,t}$, $n_{h,t}$, $h_{h,t}$ and $z_{h,t}$ represent consumption, hours worked, housing demand and liquidity services demand by households in period t , respectively. The representative household seeks to maximize

$$E_0 \sum_{i=0}^{\infty} \beta_h^i \left[\log(c_{h,t+i}) - \frac{n_{h,t+i}^{1+\phi}}{(1+\phi)} + j_{h,t+i} \log h_{h,t+i} + \chi_z \log z_{h,t+i} \right], \quad (4)$$

where $\beta_p \in (0, 1)$ is the households' subjective discount factor, ϕ refers to the inverse of the Frisch elasticity, χ_z makes reference to the preference parameter for liquidity services, and $j_{h,t}$ denotes a possibly time-varying preference parameter for housing. More precisely, $j_{h,t} = j_p \varepsilon_{h,t}$ is the exogenously time-varying households' preference parameter for housing services, where $j_h > 0$ and $\varepsilon_{h,t}$ captures exogenous housing preference shocks.

Liquidity services are derived from holding central bank digital currency, $cbdc_{h,t}$, and bank deposits, $d_{h,t}$, according to the following CES aggregator:

$$z_{h,t}(cbdc_{h,t}, d_{h,t}) = \left[cbdc_{h,t}^{(\eta-1)/\eta} + d_{h,t}^{(\eta-1)/\eta} \right]^{\eta/(\eta-1)}, \quad (5)$$

where η is the elasticity of substitution between the two forms of money. Both CBDC and deposits provide liquidity services and are thus substitutes, implying $\eta_z > 1$.¹³

The maximization of (4) is subject to the sequence of budget constraints

$$\begin{aligned} c_{h,t} + q_t(h_{h,t} - h_{h,t-1}) + cbdc_{h,t} + d_{h,t} + b_{h,t} + T_t \\ = R_{t-1}^{cbdc} \frac{cbdc_{h,t-1}}{\pi_t} + \tilde{R}_t^d \frac{d_{h,t-1}}{\pi_t} + R_{t-1}^b \frac{b_{h,t-1}}{\pi_t} + w_t n_{h,t} + \Pi_t, \end{aligned} \quad (6)$$

¹³As in Drechsler et al. 2017, the specification of the liquidity services aggregator permits to capture the degree of substitutability between public and private money.

where $b_{h,t}$ denotes holdings of the risk-free asset (which is in zero net supply), T_t lump-sum taxes, and $\Pi_t = \Omega_t + J_{r,t}$ the sum of the net transfers received from bankers, Ω_t , and profits obtained from the ownership of intermediate good producing firms. $\pi_t \equiv P_t/P_{t-1}$ denotes the gross inflation rate, q_t the real price of property, and w_t the real wage rate. $\tilde{R}_t^{cbd}$ and R_t^b denote the nominal gross interest rates on CBDC and the risk-free asset, respectively. The nominal gross interest rate on bank deposits is $\tilde{R}_t^d = R_{t-1}^d - (1 - \kappa)\Psi_t$, where R_t^d is the promised gross bank deposit return that the fraction κ of insured deposits always yields and Ψ_t is the average per unit loss rate on the fraction of uninsured deposits.

3.1.2 Banking Groups

As in [Gertler and Karadi \(2011\)](#), in each period bankers become workers with probability $1 - \theta_b$ (and workers become bankers with probability θ_b). Thus, in each period a fraction $(1 - \theta_b)$ of bankers retires, they transfer their terminal net worth to the household, and they are replaced by new bankers who continue business with an endowment (that is assumed to be a constant fraction χ_b of retiring bankers' net worth) received from the household. Therefore, the size of bankers' population remains constant over time and the (joint) aggregate accumulated net worth of (surviving and new) bankers is prevented to grow excessively and is devoted to provide equity financing to banks and pay dividends to the household.

Bankers The representative banker solves

$$V_{b,t} = \max_{e_{b,t}, \text{div}_{b,t}} \{ \text{div}_{b,t} + E_t \Lambda_{h,t+1} [(1 - \theta_b) N_{b,t+1} + \theta_b V_{b,t+1}] \}, \quad (7)$$

subject to

$$N_{b,t} = e_{b,t} + \text{div}_{b,t}, \quad (8)$$

$$N_{b,t+1} = \int_0^\infty \rho_{b,t+1}(\omega_b) dF(\omega_b) e_{b,t}, \quad (9)$$

$$\text{div}_{b,t} \geq 0, \quad (10)$$

where $\text{div}_{b,t}$ is the dividend paid to the household, $\Lambda_{h,t+1} = \beta_h \frac{\lambda_{h,t+1}}{\lambda_{h,t}}$ the stochastic discount factor of the household (with $\lambda_{h,t}$ being the Lagrange multiplier of the households' optimization problem), $N_{b,t}$ the banker's aggregate net worth, $e_{b,t}$ the net worth invested in the continuum of banks, and $\rho_{b,t}(\omega)$ is the return on equity invested in a bank with return shock ω_b .

Given that individual banks operate under constant returns to scale (see below) and bankers take returns on bank equity as given, $\rho_{b,t}$, the value function of bankers is linear in their level of net

worth. Thus, assuming that bankers always reinvest their full amount of available wealth as bank equity, the marginal value of one unit of net worth can be defined as

$$v_{b,t} = E_t \left[\Lambda_{h,t+1} (1 - \theta_b + \theta_b v_{b,t+1}) \frac{\rho_{b,t+1}}{\pi_{t+1}} \right]$$

and expression (7) can be re-written as

$$v_{b,t} N_{b,t} = \max_{e_{b,t}, \text{div}_{b,t}} [\text{div}_{b,t} + E_t \Lambda_{h,t+1} (1 - \theta_b + \theta_b v_{b,t+1}) N_{b,t+1}]. \quad (11)$$

Provided that the shadow value of one unit of bank equity satisfies $v_{b,t} > 1$, it is optimal for bankers to fully reinvest their net worth in bank equity and only distribute a terminal dividend when they retire. Expression (11) allows us to conveniently define the banker's stochastic discount factor as $\Lambda_{h,t+1} = \Lambda_{b,t+1} (1 - \theta_b + \theta_b v_{b,t+1})$.

The law of motion of bankers' aggregate net worth is given by

$$N_{b,t} = \underbrace{\theta_b \rho_{b,t} \frac{e_{b,t-1}}{\pi_t}}_{\substack{\text{Retained Earnings} \\ \text{Surviving Bankers}}} + \underbrace{(1 - \theta_b) \chi_b \rho_{b,t} \frac{N_{b,t-1}}{\pi_t}}_{\substack{\text{Initial Endowment} \\ \text{New Bankers}}}, \quad (12)$$

where χ_b is the fraction of retiring bankers' net worth with which the representative household endows new bankers. In this regard, it is useful to define transfers from retiring bankers to the household net of the initial endowment received by new bankers as $\Omega_t = (1 - \theta_b) \rho_{b,t} \frac{(e_{b,t-1} - \chi_b N_{b,t-1})}{\pi_t}$.

Banks The representative bank maximizes the net present value of bankers' equity share

$$E_t \left[\Lambda_{b,t+1} \max \left(\omega_{b,t+1} R_{t+1}^l \frac{l_{b,t}}{\pi_{t+1}} - R_t^d \frac{d_{b,t}}{\pi_{t+1}}, 0 \right) \right] - v_{b,t} e_{b,t}, \quad (13)$$

subject to a balance sheet identity and a regulatory capital requirement, respectively:

$$l_{b,t} = e_{b,t} + d_{b,t}, \quad (14)$$

$$e_{b,t} \geq \gamma_t l_{b,t}, \quad (15)$$

where $\omega_{b,t}$ is the bank-idiosyncratic asset return shock, R_t^l the gross interest rate on bank loans

to NFCs, $l_{b,t}$ bank loans to NFCs, and $d_{b,t}$ bank deposit funding. Expression (13) indicates that bank equity, $e_{b,t}$, is valued at its equilibrium opportunity cost, $v_{b,t}$, and the max operator captures bank shareholders' limited liability. Equation (14) stipulates that bank assets (i.e., loans to NFCs) are fully financed with equity, $e_{b,t}$, and bank deposit funding. Expression (15) states that, for regulatory reasons, bank equity cannot fall below a possibly time-varying fraction γ_t of bank assets. This regulatory capital requirement, γ_t , is binding in equilibrium since uninsured (or "partially covered") deposits are comparatively "less costly" to banks than equity.

Idiosyncratic return shocks, $\omega_{b,t}$: (i) are the driver of idiosyncratic bank default risk in the model, (ii) capture any exogenous sources that may affect banks' profitability, (iii) follow a log-normal distribution with a mean of one and a distribution function $F(\omega_{b,t})$ and are i.i.d. across banks (Bernanke et al. 1999), and (iv) its cross-sectional dispersion, $\sigma_{\omega,t}$, evolves stochastically over time, driven by some aggregate risk shocks (Christiano et al. 2014). The bank operates across two consecutive dates. If positive, the bank transfers its terminal net worth back to the bankers. If the bank's terminal net worth is negative the bank defaults, its equity is written down to zero and its assets are repossessed by the deposit insurance scheme. The condition for the bank not to default requires $\omega_{b,t+1} R_{t+1}^l \frac{l_{b,t}}{\pi_{t+1}} - R_t^d \frac{d_{b,t}}{\pi_{t+1}} \geq 0$, which allows us to rearrange and define the threshold for the value of $\omega_{b,t}$ below which the bank defaults as $\bar{\omega}_{b,t+1} = (R_t^d d_{b,t}) / (R_{t+1}^l l_{b,t})$. Then, we can define the probability of bank default as

$$F(\bar{\omega}_{b,t}) = \int_0^{\bar{\omega}_{b,t}} f(\omega_b; \sigma_{\omega,t}) d\omega_b = F\left[\frac{\log(\bar{\omega}_{b,t}) + \sigma_{\omega,t}^2/2}{\sigma_{\omega,t}}\right], \quad (16)$$

where $f(\omega_b; \sigma_{\omega,t})$ and $F[\cdot]$ denote the probability density function and the cumulative distribution function of the bank-idiosyncratic asset return shock $\omega_{b,t}$, respectively. Given that the risk weight of loans to NFCs is normalized to one for simplicity, it can be rearranged in expressions (14) and (15) to define the bank's leverage ratio as $d_{b,t}/l_{b,t} = (1 - \gamma_t)$. Thus, we can redefine the threshold for the value of $\omega_{b,t}$ below which the bank defaults as

$$\bar{\omega}_{b,t+1} = (1 - \gamma_t) \frac{R_t^d}{R_{t+1}^l}. \quad (17)$$

From expressions (16) and (17) it follows that the bank default probability fundamentally depends on the capital requirement and on bank profitability, measured by the relationship between the expected return on bank assets and the cost of deposit funding. As it will become clearer in Sections 4 and 5, this is important to understand how bank capitalization matters to bank riskiness, how CBDC can affect bank riskiness through its impact on bank profitability, and how does the stabilization role of optimal cyclical capital regulation operate (also in response to CBDC supply

shocks).

3.1.3 Non-Financial Corporations

Entrepreneurs obtain bank lending against CRE. This commercial real estate is rented by retailers (intermediate goods producers), who combine it with labor (through a Cobb-Douglas technology) to produce intermediate goods under monopolistic competition. Intermediate goods are purchased by final goods producers, who use them as inputs in the production process. Here, we briefly present the problem of the representative entrepreneur. For all the details on the problems of intermediate goods producers and final goods producers, we refer the reader to Appendix B.

Entrepreneurs: Borrowers Let $c_{e,t}$ represent consumption by entrepreneurs in period t . Then, entrepreneurs seek to maximize

$$E_0 \sum_{i=0}^{\infty} \beta_e^i [\log(c_{e,t+i})], \quad (18)$$

subject to a sequence of budget constraints and the corresponding borrowing limit

$$c_{e,t} + R_t^l \frac{l_{e,t-1}}{\pi_t} + q_t(h_{e,t} - h_{e,t-1}) = r_t^h h_{e,t-1} + l_{e,t}, \quad (19)$$

$$l_{e,t} \leq m_t E_t \left[\frac{q_{t+1}}{R_{t+1}^l} h_{e,t} \pi_{t+1} \right], \quad (20)$$

where $\beta_e \in (0, 1)$ is the entrepreneurs' subjective discount factor, $l_{e,t}$ denotes bank loans extended to NFCs, $h_{e,t}$ refers to commercial real estate, and r_t^h stands for the real net interest rate that entrepreneurs charge when renting commercial real estate to retailers. According to (19), in each period, entrepreneurs devote their available resources in terms of loans and rents to distribute consume, repay their debt, and accumulate commercial real estate, $h_{e,t}$. Expression (20) dictates that the borrowing capacity of entrepreneurs is tied to the value of their property collateral. In particular, they cannot borrow more than a possibly time-varying fraction $m_t = m \varepsilon_t^m$ of the expected value of their property stock, where $m \in [0, 1]$ and ε_t^m captures exogenous shocks to entrepreneurs' property collateral. As shown in Iacoviello (2005b), the assumption that $\beta_e < \beta_h$ ensures that this borrowing constraint is binding in a neighborhood of the steady state.

3.1.4 Public Authorities

Central Bank The central bank sets the nominal short-term policy rate (i.e., the interest rate on the risk-free asset) according to a Taylor-type policy rule:

$$r_t^b = \rho_r r_{t-1}^b + (1 - \rho_r) (\bar{r}^b + \alpha_\pi \tilde{\pi}_t + \alpha_Y \tilde{y}_t) + e_t^r, \quad (21)$$

where ρ_r is the interest rate smoothing parameter, $\bar{r}^b$ is the steady-state policy rate, $\alpha_\pi > 1$ determines the response of this interest rate to inflation deviations from the target, $\tilde{\pi}_t = \log(\pi_t/\bar{\pi})$, $\alpha_Y \geq 0$ measures the degree of responsiveness of the policy rate to output growth, $\tilde{y}_t = \log(Y_t/Y_{t-1})$, and e_t^r is a white noise shock to the short-term policy rate.

The central bank also issues central bank digital currency according to

$$cbdc_{cb,t} \leq \phi \bar{Y}, \quad (22)$$

and does not remunerate CBDC holdings at any point in time or

$$R_t^{cbdc} = 0, \quad (23)$$

where ϕ is a fraction (or multiple) of steady state real output. Given the assumption of a representative household (i.e., CBDC holder), expression 22 is interpretable as a limit on individual CBDC holdings. If $cbdc_{h,t}/\bar{Y} < \phi$ (i.e., expression 22 is not binding), the CBDC take-up is fully determined by expression (23) and the optimality condition for households' CBDC demand

$$\lambda_{h,t} = \beta_h E_t \left(\frac{\lambda_{h,t+1}}{\pi_{t+1}} \right) + \frac{\chi_{z,t}}{z_t} \left(\frac{z_t}{cbdc_{h,t}} \right)^{1/\eta}, \quad (24)$$

where $\lambda_{h,t}$ is the Lagrange multiplier on the budget constraint of the representative household. (i.e., $\phi_Y = 0$). In contrast, if $cbdc_{h,t}/\bar{Y} \geq \phi$, the representative household exhausts the holding limit and expression 22 becomes binding.

Central bank net profits are transferred to the government in each period and evolve as

$$\Omega_{cb,t} = cbdc_{cb,t} - \frac{cbdc_{cb,t-1}}{\pi_t}. \quad (25)$$

Prudential Authority The prudential authority sets the regulatory capital requirement according to a rule

$$\gamma_t = \rho_\gamma \gamma_{t-1} + (1 - \rho_\gamma) (\gamma + \gamma_x \tilde{X}_t), \quad (26)$$

where ρ_γ is the capital requirement smoothing parameter, γ captures structural (i.e., steady-state) capital requirements and the term $\gamma_x \tilde{X}_t$ measures cyclical capital requirements, with the CCyB (or macroprudential policy) parameter γ_x capturing the degree of responsiveness of γ_t to changes in a macro-financial indicator of the choice of the regulator, $\tilde{X}_t$.

Deposit Insurance Scheme The DIS operates as follows to ensure that, upon default of a bank, households are fully refunded for the losses associated with their insured deposit holdings. When a bank defaults its assets are transferred to the DIS. However, due to a proportional repossession cost μ_b (also interpretable as bank resolution costs) only $(1 - \mu_b) \omega_{b,t+1} R_{t+1}^l \frac{l_{b,t}}{\pi_{t+1}}$ is effectively repossessed by the DIS. Insured deposits are fully covered by complementing a fraction κ of repossessed bank assets with lump-sum taxes and central bank net profits. Thus, lump-sum taxes collected by the DIS are given by

$$T_t = \kappa \Psi_t \frac{d_{h,t-1}}{\pi_t} - \Omega_{cb,t}. \quad (27)$$

where the term $\Psi_t \frac{d_{h,t-1}}{\pi_t} = \left[(R_{t-1}^d d_{b,t-1}) \frac{F(\bar{\omega}_{b,t})}{\pi_t} - (1 - \mu_b) R_t^l l_{b,t-1} \frac{G_t(\bar{\omega}_{b,t})}{\pi_t} \right]$ refers to the total losses incurred by households on deposits that are not covered with repossessed bank assets. $G(\bar{\omega}_{b,t})$ refers to the share of total bank assets that end up in default.¹⁴ Remaining repossessed bank asset returns, $(1 - \kappa) (1 - \mu_b) R_t^l l_{b,t-1} \frac{G_t(\bar{\omega}_{b,t})}{\pi_t}$, are devoted to partially cover the losses incurred by households for their holdings of uninsured deposits. Given that, in each period, the risk-free asset is assumed to be in zero net supply, $b_{h,t} = 0$, in this model expression (27) is equivalent to the intertemporal budget constraint of the government.

3.1.5 Aggregation, Market Clearing and Net Output

In equilibrium, all markets clear. The supply is endogenous in all markets with the exception of real estate supply, which is specified as a fixed endowment that is normalized to one

$$\bar{H} = h_{h,t} + h_{e,t}. \quad (28)$$

In the case of the final goods market, the aggregate resource constraint dictates that the income generated in the production process is fully spent in the form of aggregate final consumption, C_t , and resolution costs, which represent a deadweight loss for society:

$$Y_t = C_t + \mu_b R_t^l l_{b,t-1} \frac{G_t(\bar{\omega}_{b,t})}{\pi_t}, \quad (29)$$

¹⁴See Appendix B for the analytical expression of $G(\bar{\omega}_{b,t})$.

where $C_t = c_{h,t} + c_{e,t}$. As standard in this strand of the literature, we differentiate between total output (expression 29) and net output, defined as total output net of the deadweight loss:

$$\tilde{Y}_t = Y_t - \mu_b R_t^l l_{b,t-1} \frac{G_t(\bar{\omega}_{b,t})}{\pi_t}, \quad (30)$$

The definition of real GDP given by expression 30 is convenient for the purpose of "uncovering" the real effects of capital requirements, which under expression 29 may be blurred by the fact that the bank default probability (and bank resolution costs) is countercyclical and determined, to a large extent, by the capital requirement itself. Note that in this model, net output is equal to aggregate consumption.

3.2 Calibration

We follow a three-stage strategy in order to calibrate the model to quarterly data of the euro area economy. Data targets have been taken from two recent macro-banking models that have also been calibrated to quarterly euro area data for a similar period; Mendicino et al. (2020) and Burlon et al. (2024).

First, several parameters are set following convention (Table 4A). The inverse of the Frisch elasticity of labor, the elasticity of substitution between intermediate goods and the loan-to-value on commercial (real estate) mortgages, m^h , are fixed to conventional values of 1, 6 and 0.7, respectively. The elasticity of substitution between bank deposits and CBDC is set to a value of 3.58 (Burlon et al. 2024). The Calvo parameter is set to 0.75, The standard deviation of bank asset return shocks to 0.029, and the three parameters of the Taylor rule (i.e., ρ_r , α_Y , and α_π) to values of 0.75, 0.1 and 1.5, respectively (Mendicino et al. 2020). The property share in production is fixed to a value of 0.03 (Iacoviello 2005b).

Second, another group of parameters is calibrated by using steady state targets (Tables 4B and 5A). The households' discount factor, $\beta_h = 0.9942$, is chosen such that the annual interest rate on the risk equals 2.32%. The Entrepreneurs' discount factor is set to 0.9862, in order to generate an annualized bank deposits-to-GDP ratio of 6.31. Households' weights on liquidity services, χ_z , and on housing utility, j , have been calibrated to match the annualized return on deposits and the households' property wealth-to-GDP ratio, respectively. Based on the Basel III Accords, we set the regulatory (structural) capital requirement, γ , to 8%. In line with existing evidence for the euro area, the share of insured deposits is fixed to a value of 0.54. The bank bankruptcy cost parameter is set to 0.3 to generate a recovery rate of around 70% of assets held by banks upon default (Mendicino et al. 2020, 2024).¹⁵ The survival rate of bankers, $\theta_b = 0.77$, is chosen

¹⁵ Alderson and Betker (1995) estimate liquidation costs to represent 36% percent of assets, whereas Granja et al.

to match a bank price-to-book ratio of 1.148; whereas the mean standard deviation of i.i.d. bank-idiosyncratic return shocks is set to a value of 0.0287 such that the annual bank default rate equals 0.665. The fraction χ_b of retiring bankers' net worth is fixed to a value of 0.946 to match the annual bank return on equity (RoE). The gross inflation target, $\bar{\pi}$, is set to 1.005 to generate an annualized inflation rate of 2%, in line with the Eurosystem's quantitative objective of price stability. The CBDC supply parameter, ϕ , is fixed to a value of 0 as in the baseline scenario there is no issuance of central bank digital currency.

Table 4: Baseline calibration

Parameter	Description	Value	Target ratio/Source
(A) Preset Parameters			
φ	Inverse of the Frisch elasticity	1.000	Standard
ε	Elast. of subst. intermediate goods	6.000	Standard
m	LTV borrowers' property	0.700	Standard
η	Elast. of subst. liquidity services	3.580	Burlon et al. (2024)
θ	Calvo probability	0.750	Mendicino et al. (2020)
ρ_r	Taylor rule: smoothing parameter	0.750	Mendicino et al. (2020)
α_π	Taylor rule: inflation response param	1.500	Mendicino et al. (2020)
α_y	Taylor rule: GDP growth response param	0.100	Mendicino et al. (2020)
σ_ω	Std. bank risk shock	0.029	Mendicino et al. (2020)
ν	Property share in production	0.030	Iacoviello (2005b)
(B) First moments			
β_h	Savers' discount factor	0.9942	$(\beta_h^{-1} - 1)x \ 400 = 2.320$
β_e	Borrowers' discount factor	0.9862	$(\bar{R}^d - 1)/x \ 400 = 0.558$
χ_z	Savers' liquidity services weight	0.0634	$\bar{d}_b/\bar{Y} = 6.3106$
j	Savers' housing services weight	0.0170	$\bar{q}\bar{h}_h/\bar{Y} = 2.802$
γ	Regulatory capital requirements	0.0800	$\bar{e}_b/\bar{l}_b = 0.080$
κ	Share of insured deposits	0.5400	$\kappa = 0.540$
μ_b	Complementary of recovery rate	0.300	$\mu_b = 0.300$
θ_b	Survival rate of bankers	0.7700	$\bar{v}_b = 1.148$
$\bar{\sigma}_b$	Mean std. of iid bank shocks	0.0287	$\bar{F}(\bar{\omega})x \ 400 = 0.665$
χ_b	Transfer from HH to bankers	0.9460	$(\bar{\rho}_b - 1)x \ 400 = 7.066$
$\bar{\pi}$	Gross inflation target	1.0050	$(\bar{\pi} - 1)x \ 400 = 2.000$
ϕ	CBDC holding limit	0.0000	$\bar{c}bdc_{cb}/\bar{Y} = 0.000$
(C) Second moments			
σ_A	Std. TFP shock	0.0120	$\sigma_Y \ x \ 100 = 2.631$
σ_{m_H}	Std. NFC collateral shock	0.0013	$\sigma_l/\sigma_Y = 3.138$
σ_h	Std. housing pref. shock	0.0020	$\sigma_{(r^l - r^d)} / \sigma_Y = 0.087$
σ_{r^b}	Std. monetary policy shock	0.0003	$\sigma_{r^l} / \sigma_Y = 0.122$

Notes: All series in Euros are seasonally adjusted and deflated. Data targets for quarterly data of the euro area have been taken from [Mendicino et al. \(2020\)](#), [Muñoz \(2021\)](#) and [Burlon et al. \(2024\)](#). The standard deviation of GDP is in quarterly percentage points. Abbreviations HH, NFC and TFP refer to households, non-financial corporations (entrepreneurs) and total factor productivity, respectively.

[\(2017\)](#) find that the average FDIC loss from selling a failed bank is 28% of assets

Third, the size of shocks affecting the dispersion of key aggregates are calibrated to improve the fit of the model to the data in terms of relative volatilities (Tables 4C and 5B). The size of TFP shocks, NFC collateral shocks, housing preference shocks and monetary policy shocks have been calibrated to match the second moment (in terms of relative standard deviations) of GDP, bank loans, the bank lending spread and the interest rate on bank loans, respectively.

The autoregressive coefficients in the AR(1) processes followed by all shocks are set equal to 0.90. Under the baseline scenario, cyclical capital regulation remains inactive (i.e., $\gamma_x = 0$ and $\rho_\gamma = 0$).

Table 5: Model fit

Variable	Description	Model	Data
(A) First moments			
$(\beta_h^{-1} - 1)x$ 400	Real risk-free rate	2.334	2.320
$(\bar{\rho}_b - 1)x$ 400	Bank equity return	7.056	7.066
$(\bar{R}^d - 1)x$ 400	Bank deposit rate	0.558	0.558
$\bar{F}(\bar{\omega})x$ 400	Bank default rate	0.666	0.665
$(\bar{\pi} - 1)x$ 400	Inflation target	2.000	2.000
$\bar{v}_b$	Bank price-to-book ratio	1.030	1.148
$\bar{e}_b/\bar{l}_b$	Regulatory capital requirements	0.080	0.080
$\bar{d}_b/\bar{Y}$	Bank deposits-to-GDP ratio	6.315	6.311
κ	Share of insured deposits	0.540	0.540
μ_b	Complementary of recovery rate	0.300	0.300
$\bar{c}b\bar{d}c_{cb}/\bar{Y}$	CBDC-to-GDP ratio	0.000	0.000
$\bar{q}\bar{h}_h/\bar{Y}$	HH property wealth-to-GDP ratio	2.802	2.802
(B) Second moments			
σ_Y x 100	Std(GDP) x 100	2.630	2.631
σ_l / σ_Y	Std. bank lending/Std(GDP)	3.369	3.138
σ_d / σ_Y	Std. bank deposits/Std(GDP)	3.369	3.123
$\sigma_{(r^l - r^d)} / \sigma_Y$	Std. bank lending spread/Std(GDP)	0.088	0.087
σ_{r^l} / σ_Y	Std. bank lending rate/Std(GDP)	0.148	0.122
σ_{r^d} / σ_Y	Std. bank deposit rate/Std(GDP)	0.103	0.043

Notes: All series in Euros are seasonally adjusted and deflated. Data targets for quarterly data of the euro area have been taken from [Mendicino et al. \(2020\)](#), [Muñoz \(2021\)](#) and [Burlon et al. \(2024\)](#). The standard deviation of GDP is in quarterly percentage points. Abbreviation HH refers to households.

4 Transmission

This section studies the main transmission mechanisms of CBDC in this economy and illustrates how the model captures the main empirical findings presented in Section 2.

4.1 Transmission Mechanisms

First, we distill the transmission of CBDC to banks and the macroeconomy into four main channels: bank deposit substitution, bank profitability, bank disintermediation, and fiscal expansion.

Figure 4 presents the workings of each channel in each of the four rows. It does so by plotting the steady state level of selected aggregates for a CBDC supply parameter, ϕ , that ranges from 0 to 1.5. Recalling expression (22), this implies a CBDC-to-GDP ratio ranging from 0% to 150%. Due to the substitutability between CBDC and bank deposits (expression 5), banks experience deposit outflows as the amount of CBDC in circulation goes up. That has two consequences. First, liquidity services increase as the decline in bank deposits is less than proportional to the increase in CBDC. This follows from the fact that such substitutability is imperfect. Second, the interest rate on deposits escalates as households's supply of deposit funding recedes.

Such upward pressure on the deposit rate negatively affects bank profitability. The cost of bank deposit funding increases and so does the bank weighted average cost of capital (WACC). Bank profitability (proxied by the lending spread) moderately deteriorates with the quantity of CBDC. In line with the evidence, this effect has a very moderate impact on the bank default probability.¹⁶

Banks react to the jump in the WACC by exerting an upward pressure on the lending rate. They do so by restricting credit supply. This response has several consequences. First, given the capital requirement, banks also readjust bank equity downwards. Second, aggregate demand is negatively affected. Private consumption recedes and NFCs reduce their investments in CRE. Consequently, property prices fall.

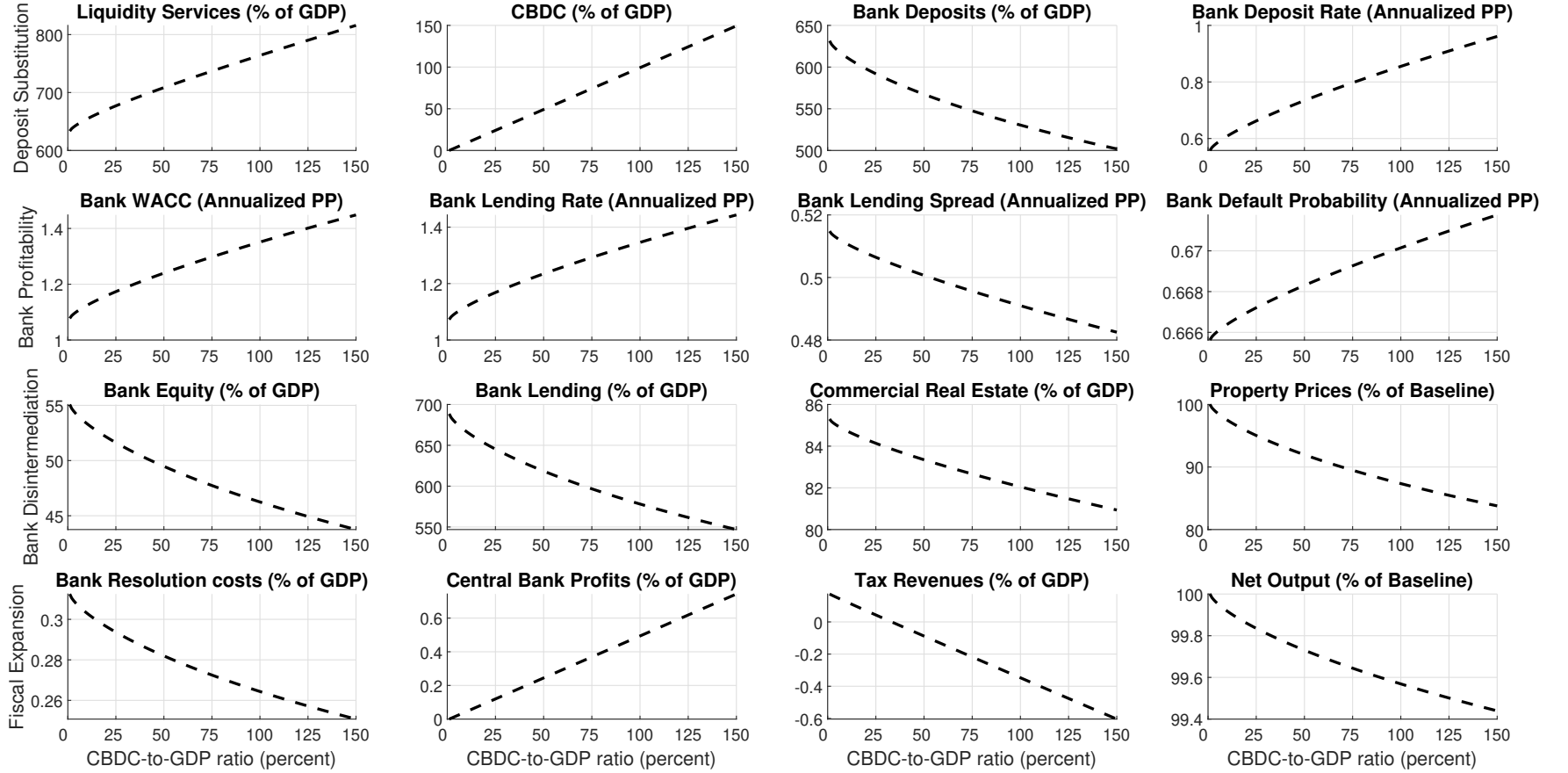
The corresponding adverse impact on net output is very moderate, partly due to a fiscal expansion induced by CBDC through two sub-channels. The aggregate economic cost of bank risk failure (captured by the deadweight loss in expression 29) decreases with CBDC as bank lending goes down. Moreover, taxes levied on households decline as central bank profits soar. That is, a CBDC-induced increase in seigniorage revenues (expression 25) relaxes the intertemporal government budget constraint and fosters private consumption.

4.2 Bank Capitalization and CBDC Effects on Bank Riskiness

According to the evidence, CBDC has a moderate but visible and persistent impact on the default probability (proxied by CDS spreads) of those banks whose capital buffer is below the median (Figure 2).

¹⁶Recall expressions (16) and (17) for a better understanding of the mechanism through which the lending spread affects the bank default probability via its impact on $\bar{\omega}_{b,t}$, the threshold below which the bank defaults.

Figure 4: Transmission mechanisms and steady state effects of CBDC issuance



Notes: Effects on the steady state level of selected variables from ceteris paribus changes in CBDC policy parameter, ϕ . Each variable is expressed as a percentage of quarterly real GDP (proxied by net output), as annualized percentage points or as a percentage of its baseline calibration level.

To assess the effects of CBDC on bank riskiness through the lens of our model we differentiate between two versions of the baseline calibration model which only differ from one another in the level of the capital ratio. We distinguish between a case in which $\gamma \times 100 = 6\%$ (i.e., below the baseline level or "median" of 8%) and a case in which the capital ratio is equal to 10% (i.e., above the "median").

Figure 5 illustrates the steady state effects of CBDC on bank riskiness (measured by the bank default probability). Panel A displays the steady state effects on the bank default rate of ceteris paribus changes in parameters γ and ϕ . The main conclusions follow from expressions (16) and (17). First, the bank default probability decreases with the bank capital ratio, with the latter being a key determinant of the former. Second, the impact of CBDC on bank riskiness is marginal (if anything) as it indirectly operates through the moderate impact of the former on the bank lending spread. The magnitude of this effect depends on the bank capital ratio and is only tangible if the CBDC-to-GDP ratio is sufficiently high.

This point is made clear in Panel B, which plots the steady state effects on the bank default probability of ceteris paribus changes in the CBDC-to-GDP ratio under the two versions of the model. Under a bank capital ratio of 10%, CBDC does not affect long-term bank riskiness, regardless of the amount of central bank digital currency in circulation. Under a bank capital ratio of 6%, CBDC very moderately affects the bank default probability. A 0.1 percentage point increase in the steady state bank default rate requires a quantity of CBDC exceeding 500% of quarterly GDP in the long term. Given the range of values possibly being considered under the digital euro project, this amount of CBDC in circulation is basically ruled out in practice.

Figure 6 displays the impulse responses of key selected aggregates to a persistent but transitory CBDC supply shock under the two versions of the model. To allow for this type of shocks we redefine expression (22) for the purpose of this exercise as

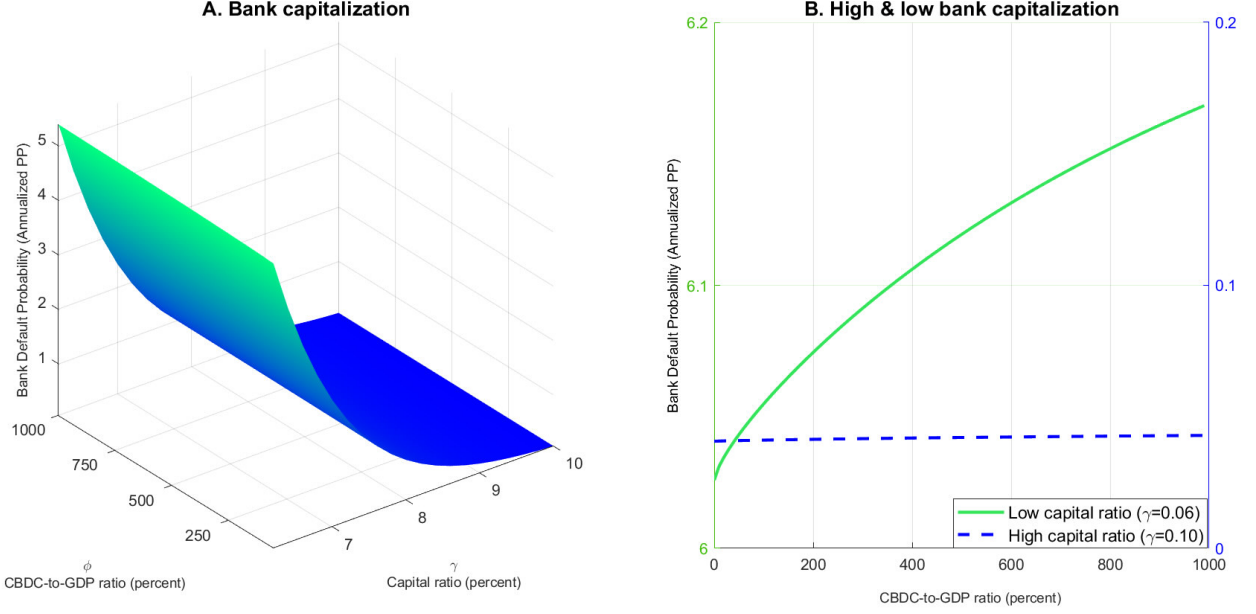
$$cbdc_{cb,t} \leq \phi \varepsilon_t^\phi \bar{Y}, \quad (31)$$

where ε_t^ϕ captures exogenous shocks to the CBDC supply.¹⁷

In response to the same CBDC supply shock, deposits fall by more under the low bank capital ratio scenario (solid line). Consequently, the upward pressure on the deposit rate is more pronounced in this case. As a result of this, the probability of bank default soars under this scenario by more than under the high bank capital ratio scenario (dashed line). In fact, the bank default rate is

¹⁷The size of these shocks, σ_ϕ , is set equal to 0.1. As for the rest of the shocks that hit this model economy under the baseline calibration, the autorregressive coefficient in the AR(1) process followed by these shocks, ρ_ϕ , is set to a value of 0.9.

Figure 5: Implications of bank capitalization for CBDC effects on bank riskiness



Notes: Panel A displays the effect on the steady state bank default probability from simultaneous ceteris paribus changes in parameters ϕ and γ . Panel B plots the effect on the steady state bank default probability from ceteris paribus changes in parameter ϕ under bank capital ratios of 6% (solid line) and 10% (dashed line).

barely affected by the shock in the latter case. Any adverse impact of CBDC supply shocks on bank lending diminishes with the level of bank capitalization.

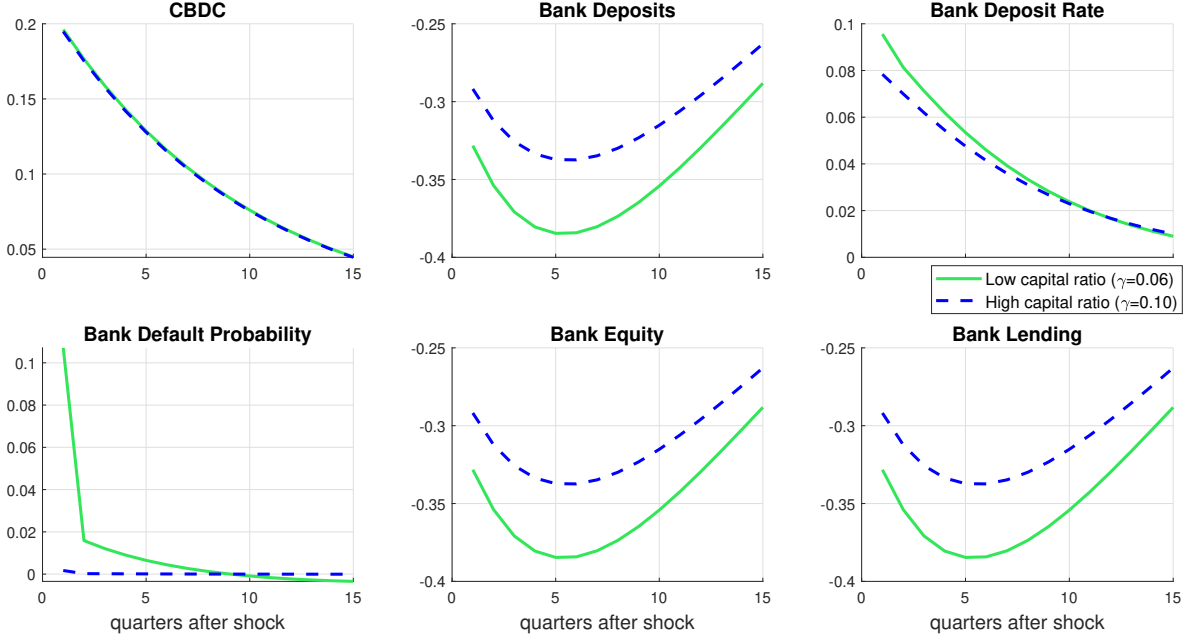
5 Optimal Capital Requirements & CBDC Holding Limits

This section studies the interactions between CBDC and optimal bank capital regulation. Subsection 5.1 describes our approach to welfare analysis, including the design of CBDC regimes and optimal capital regulation scenarios. Subsection 5.2 characterizes optimal structural capital requirements and the holding limit required to neutralize the impact of CBDC on such optimal requirements. Subsection 5.3 performs a similar study for the case of optimal cyclical capital regulation. Subsection 5.4 evaluates the impact of optimal structural and cyclical capital regulations on the main macroeconomic effects through which CBDC has welfare consequences.

5.1 Welfare Analysis

To study optimal (i.e., welfare-maximizing) capital requirement rules within the class (26), we propose a measure of social welfare specified as a weighted average of the expected life-time utility of savers and borrowers. This measure is maximized with respect to the corresponding capital

Figure 6: IRFs to a CBDC supply shock. High & low bank capitalization



Notes: Variables are expressed in percentage deviations from the steady state with the exceptions of CBDC, the deposit rate and the bank default probability, which are shown as absolute deviations from the steady state, with all of them except for the first one being annualized and expressed in percentage points. The solid and dashed lines refer to the scenarios under which $\gamma = 0.06$ and $\gamma = 0.10$, respectively. Parameter ϕ is set to a value of 1.9651, such that the steady-state CBDC-to-GDP ratio corresponds to the one that prevails under the unconstrained CBDC scenario. The size and persistence parameters of this shock (i.e., σ_ϕ and ρ_ϕ) are fixed to values of 0.1 and 0.9, respectively.

requirement parameter/s. Formally:

$$\arg \max_{\Theta} V_0 = \omega_h V_0^h + (1 - \omega_h) V_0^e, \quad (32)$$

where $V_0^h = E_0 \sum_{i=0}^{\infty} \beta_h^i u(c_{h,t+i}, h_{h,t+i}, n_{h,t+i}, z_{h,t+i})$ and $V_0^e = E_0 \sum_{i=0}^{\infty} \beta_e^i u(c_{e,t+i})$ are the expected life-time utility functions of households (savers) and entrepreneurs (borrowers), respectively. ω_h denotes the utility weight of households and Θ refers to the vector of policy parameters within policy rule (26) with respect to which the objective function is maximized. The Problem (32) is subject to all equilibrium conditions of the model.

To assess the potential effects of central bank digital currency on optimal bank capital regulation, we consider three policy-relevant CBDC regimes. Regime "A", under which there is no CBDC supply (i.e., $\phi = 0$); regime "B", under which demand for unremunerated CBDC is fully satisfied (also referred to as the unconstrained CBDC regime); and regime "C", under which there is a calibrated limit on individual CBDC holdings. We set parameter ϕ under regime "C" to a value

of 0.3, so as to roughly neutralize the impact of CBDC on bank riskiness and optimal bank capital regulation (and the associated welfare gains) while ensuring wide CBDC adoption. This corresponds to an amount of CBDC in circulation of 30%, which is in the range of values typically found in the academic literature and discussed in the policy debate. According to [Burlon et al. \(2024\)](#), the optimal quantity of CBDC in the euro area lies between 15% and 45% of quarterly GDP. According to [Bindseil and Panetta \(2020\)](#), "a per capita amount of EUR 3,000.. could be interpreted as covering the average monthly net income of euro area households, such that the normal payment function of money would be covered." If all citizens in the euro area were to hold this maximum individual level of CBDC in 2024, the amount of central bank digital currency in circulation would be roughly 28% of quarterly GDP.¹⁸ Through the lens of the model proposed in [Bidder et al. \(2024\)](#), the optimal limit on individual CBDC holdings in the euro area ranges from EUR 1,500 to EUR 2,500.

In each case, we consider two scenarios; the baseline capital regulation scenario (i.e., $\gamma = 0.08$; $\gamma_x = 0$; $\rho_\gamma = 0$) and the optimal capital regulation scenario. Subsection 5.2 studies optimal structural capital requirements. In this case, the optimal capital regulation scenario is referred to one in which problem (32) is solved for parameter γ . Subsection 5.3 focuses on optimal cyclical capital requirements and takes the optimal capital regulation scenario as one in which problem (32) is simultaneously solved for parameters γ , γ_x and ρ_γ . Each of the different CBDC and bank capital regulation scenarios are compared against the baseline calibration scenario (i.e., $\phi = 0$; $\gamma = 0.08$; $\gamma_x = 0$; $\rho_\gamma = 0$).

5.2 Optimal Structural Capital Requirements

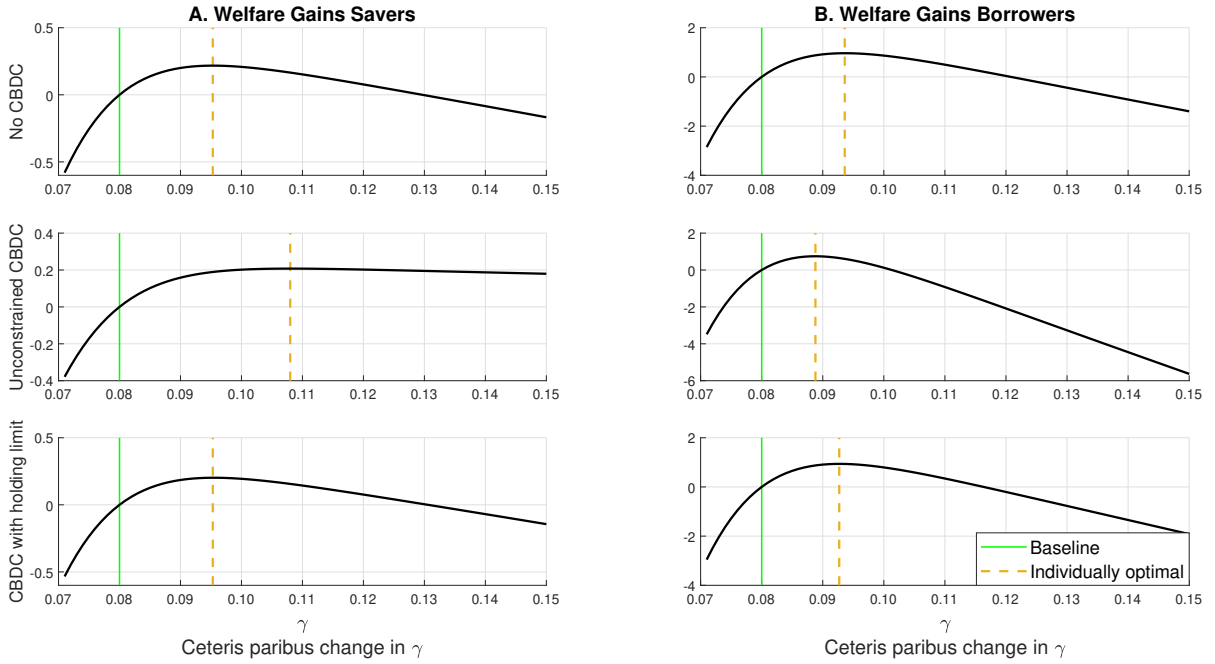
First, we study the implications of CBDC for the effects of structural capital requirements on savers and borrowers' welfare. Figure 7 plots the individual welfare gains of changing the value of parameter γ under each of the three CBDC regimes. Regardless of the CBDC amount in circulation, there is an optimal capital requirement. This is the case as there is a macroeconomic trade-off from raising bank capital requirements that affects both agent types. On the one hand, the bank default probability drops causing the aggregate economic cost of bank risk failure (captured by the deadweight loss reflected in expression 29) to recede and aggregate demand to expand. Up to a certain point, such decline in bank riskiness encourages banks to extend more loans. On the other hand, the weighted average cost of capital (WACC) of banks soars as the weight of the costlier funding source (i.e., equity) increases in the funding mix. For this reason, beyond a certain

¹⁸This number has been obtained after having rounded up the size of the population in the euro area to 350 million citizens and average quarterly GDP in 2024 to EUR 3,750 billions. In practice, the CBDC-to-GDP ratio under a EUR 3,000 limit on individual holdings would likely be lower than 28% for at least two reasons. First, not all citizens in the euro area hold money and have bank accounts. Second, due to their preferences and/or to their availability of funds, not all citizens are likely to exhaust the regulatory limit ([Adalid et al. 2022](#)).

capital requirement level, bank lending and real economic activity recede.¹⁹

An unconstrained issuance of CBDC (regime B) affects this trade-off differently, depending on the agent type under consideration. As CBDC moderately lowers private consumption, households find optimal to have a tightening of capital requirements that helps in offsetting such effect by reducing the aggregate economic cost of bank risk failure (proxied by the deadweight loss) and lump-sum taxes. Given that issuing CBDC negatively impacts bank lending supply, entrepreneurs find optimal to have a relaxation of capital requirements that compensates for such effect by encouraging banks to extend more loans (see Appendix C).

Figure 7: Welfare gains of structural capital requirements (ceteris paribus changes in γ)



Notes: Second-order approximation to the unconditional individual welfare gains of savers and borrowers (expressed in percentage permanent consumption) as a function of structural capital requirement parameter, γ , under each of the three CBDC regimes. The solid and dashed vertical lines indicate the structural capital requirement under the baseline calibration and the one for which welfare gains of the corresponding agent type are maximized, respectively.

Adequately calibrating the amount of CBDC in circulation via a holding limit (regime C) allows to roughly neutralize the impact of CBDC on optimal structural capital requirements and on the welfare gains that can be attained through that regulation.

Then, we assign a value to parameter ω_h and compute, for each CBDC regime and capital requirement scenario, social welfare gains and the bank default probability. Welfare gains are computed by comparing each of these scenarios against the baseline calibration scenario (i.e., $\phi = 0$; $\gamma = 0.08$;

¹⁹For further details on the channels through which these effects are transmitted to the economy, see Appendix C.

$\gamma_x = 0$; $\rho_\gamma = 0$). Table 6 reports this information along with the quantity of CBDC and the structural capital requirement that prevails in each scenario. We set ω_h to a value of 1 mainly for empirical reasons. First, our empirical findings suggest that optimal capital needs increase with CBDC to absorb the potential additional layer of bank risk. Second, there are no official statistics for it but the share of entrepreneurs in the euro area population is estimated to be very small. For this reason, we opt for a sensible value for ω_h given our evidence and refer the reader to Appendix C for an assessment of how social welfare gains vary with parameter ω_h under the case of a CBDC holding limit (regime C) and optimal capital requirements. To avoid the challenge of having to assign a value to ω_h , we could have opted for an alternative modelling choice by which entrepreneurs (same as bankers) are a special member of households (e.g., Mendicino et al. 2020). However, while that assumption would not qualitatively affect our main findings, it would make it more challenging to identify and assess the key individual welfare effects and trade-offs induced by CBDC through the bank capital regulation channel. Fourth, given that households reap most of the benefits of CBDC, focusing on this case also helps to better understand the extent to which a CBDC holding limit restricts the welfare gains that CBDC holders can attain.

Table 6: Welfare gains of CBDC and optimal structural capital requirements

CBDC Regime & Scenario	CBDC Adoption ($CBDC_t \times 100/Y_t$)	Capital Requirement ($\gamma \times 100$)	Welfare Gains ($\lambda \times 100$)	Bank Riskiness ($\bar{F}(\bar{\omega}) \times 400$)
A) No CBDC				
(i) γ (baseline)	0.00%	8.0%	0.000%	0.6656 <i>pp</i>
(ii) γ^* (optimal)	0.00%	9.5%	0.217%	0.0868 <i>pp</i>
B) Unconstrained CBDC				
(i) γ (baseline)	196.51%	8.0%	3.549%	0.6732 <i>pp</i>
(ii) γ^* (optimal)	204.80%	10.8%	3.764%	0.0114 <i>pp</i>
C) CBDC with holding limit				
(i) γ (baseline)	30.00%	8.0%	0.852%	0.6675 <i>pp</i>
(ii) γ^* (optimal)	30.00%	9.5%	1.056%	0.0872 <i>pp</i>

Notes: For each of the three CBDC regimes and the two structural capital requirement scenarios, the table reports the CBDC-to-GDP ratio (in percent), the structural capital requirement (in percent), a second-order approximation to the social welfare gains (in percentage permanent consumption) and the bank default probability (in annualized percentage points). Parameter ω_h is fixed to a value of 1. Policy parameters marked with an asterisk correspond to those for which social welfare is maximized.

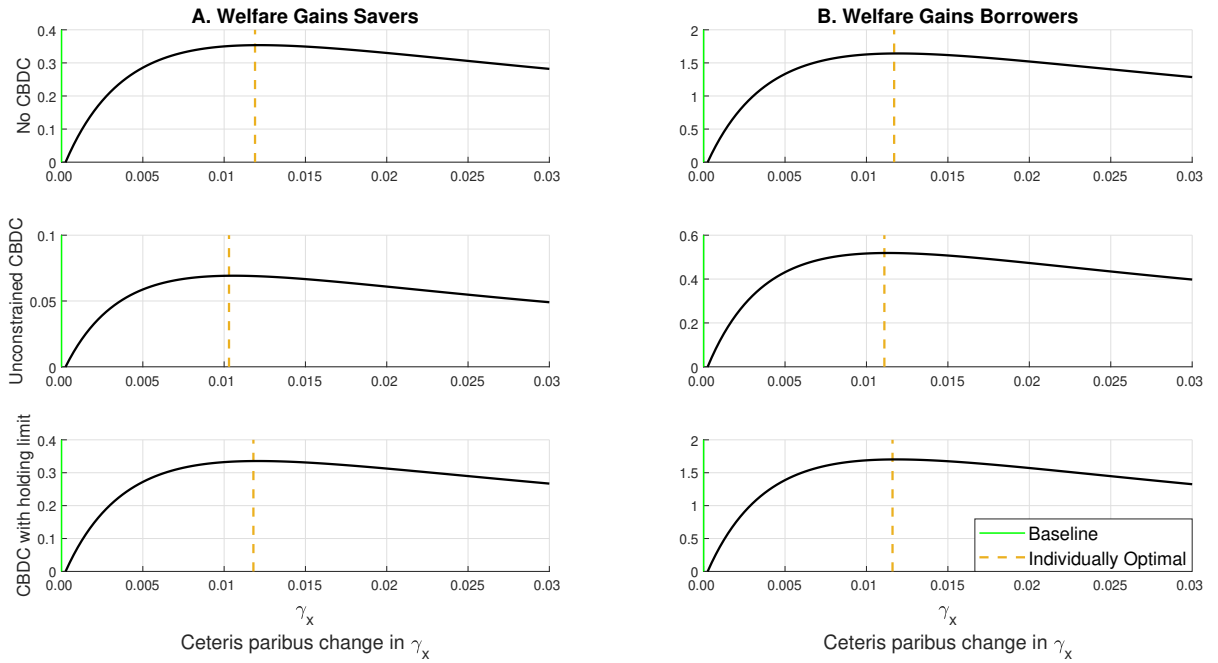
Regardless of the CBDC regime, raising the capital requirement to its optimal level induces significant welfare gains (in this case of around 0.2%) and prominently reduces the bank default probability to around 0.1 pp, making of bank failure a rare event. Under Regime B, CBDC induces very large welfare gains and bank riskiness is moderately above that of alternative scenarios. Households optimally tolerate a higher level of bank riskiness as CBDC reduces its aggregate economic cost. In particular, under regime B bank resolution costs and taxes fall as bank assets decline and central bank profits soar, respectively. A properly calibrated limit on CBDC holdings

(regime C) roughly neutralizes the impact of CBDC on bank riskiness and optimal bank capital regulation while ensuring that welfare gains induced by CBDC are still significant, even if lower than in the absence of a holding limit.

5.3 Optimal Cyclical Capital Requirements

Similarly, this subsection analyzes the implications of CBDC for the effects of cyclical capital requirements on savers and borrowers' welfare. Figure 8 plots the individual welfare gains of changing the value of parameter γ_x under each of the three CBDC regimes for the case in which indicator $\tilde{X}_t$ is the forward-looking growth rate of the bank lending spread and smoothing parameter ρ_γ is equal to 0.9. These choices are based on a search analysis identical to the one proposed in Muñoz and Smets (2024) and our findings are consistent with those of such work.

Figure 8: Welfare gains of cyclical capital requirements (ceteris paribus changes in γ_x)



Notes: Second-order approximation to the unconditional individual welfare gains of savers and borrowers (expressed in percentage permanent consumption) as a function of the CCyB parameter, γ_x , under each of the three CBDC regimes. The solid and dashed vertical lines indicate the CCyB parameter value under the baseline calibration and the one for which welfare gains of the corresponding agent type are maximized, respectively.

Regardless of the CBDC quantity, there is an optimal cyclical capital requirement (Figure 8). Under regime B, optimal cyclical capital requirements are less responsive and yield more moderate welfare gains than in the absence of CBDC. This is the case as CBDC induces a macroeconomic stabilization effect (Burlon et al. 2024) that, arguably, affects the optimal degree of stabilization to be attained by other policies, including cyclical bank capital regulation. Adequately calibrating

the amount of CBDC in circulation via a holding limit (regime C) allows to roughly neutralize the impact of CBDC on optimal cyclical capital requirements and on the welfare gains that can be attained through that regulation.

Table 7 reports the welfare gains attained under each CBDC regime and capital requirement scenario, against the baseline scenario. There are three findings that stand out. First, if the amount of CBDC in circulation is not "very large" (e.g., regimes A and C) optimal cyclical capital regulation yields significant welfare gains, which in this case range from around 0.15% to 0.35% depending on whether the structural capital requirement is also at its optimal level or not. Second, such welfare gains decrease with the quantity of CBDC due to the substitutability between the stabilization capacity of the CCyB and that of CBDC. Third, solving problem 32 also with respect to parameter γ (i.e., optimal capital requirement scenario) only makes these welfare gains increase marginally.

Table 7: Welfare gains of CBDC and cyclical capital requirements

Scenario	CBDC Adoption ($CBDC_t \times 100 / Y_t$)	Capital Requirement ($\gamma \times 100$)	CCyB (γ_x^*)	Welfare Gains ($\lambda \times 100$)
A) No CBDC				
(i) γ (baseline)	0.00%	8.0%	0.0119	0.354%
(ii) γ^* (optimal)	0.00%	7.76%	0.0113	0.361%
B) Unconstrained CBDC				
(i) γ (baseline)	196.51%	8.0%	0.0103	3.621%
(ii) γ^* (optimal)	204.80%	10.80%	0.0000	3.764%
C) CBDC with holding limit				
(i) γ (baseline)	30.00%	8.0%	0.0118	1.191%
(ii) γ^* (optimal)	30.00%	7.71%	0.0111	1.200%

Notes: For each of the three CBDC regimes and the two structural capital requirement scenarios, the table reports the CBDC-to-GDP ratio (in percent), the structural capital requirement (in percent), the CCyB parameter and a second-order approximation to the social welfare gains (in percentage permanent consumption). Parameter ω_h is fixed to a value of 1. Policy parameters marked with an asterisk correspond to those for which social welfare is maximized. In each case, $\tilde{X}_t$ is the forward-looking growth rate of the bank lending spread and smoothing parameter ρ_γ is set to a value of 0.9.

To better understand how the stabilization capacity of cyclical capital regulation works in the model, Figure 9 displays the impulse responses of selected aggregates to an exogenous CBDC supply shock under regime C. Under the baseline calibration capital requirements (i.e., $\gamma = 0.08$; $\gamma_x = 0$; $\rho_\gamma = 0$), the issuance of CBDC exerts an upward pressure on the deposit rate as households' supply of deposit funding recedes. On impact, bank profitability deteriorates causing a decline in bank equity and a jump in the bank default probability. The aggregate economic cost of bank risk failure (proxied by the deadweight loss) soars adversely affecting net output and investment in CRE (which causes property prices to fall). Under the optimal capital requirement rule (i.e.,

Figure 9: IRFs to a CBDC supply shock with a CBDC holding limit. Optimal capital requirements



Notes: Variables are expressed in percentage deviations from the steady state with the exceptions of bank capital requirements, the bank deposit rate and the bank default probability, which are shown as absolute deviations from the steady state and are expressed in percentage points, with all of them except for the first one being annualized. Under regime C (CBDC holding limit), the dashed and dotted lines refer to the baseline capital requirement scenario and the optimal capital requirement rule scenario, respectively. Indicator $\tilde{X}_t$ is the forward-looking growth rate of the bank lending spread. The size of the shock, σ_ϕ , is normalized to 0.01.

$\gamma^* = 0.0771$; $\gamma_x^* = 0.0111$; $\rho_\gamma^* = 0.9$), the CCyB starts being built one period ahead of the bank lending spread begins to recover. That action strengthens bank resilience (the bank default probability declines) and, through that channel, lowers the aggregate economic cost of bank risk failure and sustains private consumption and real estate investment.

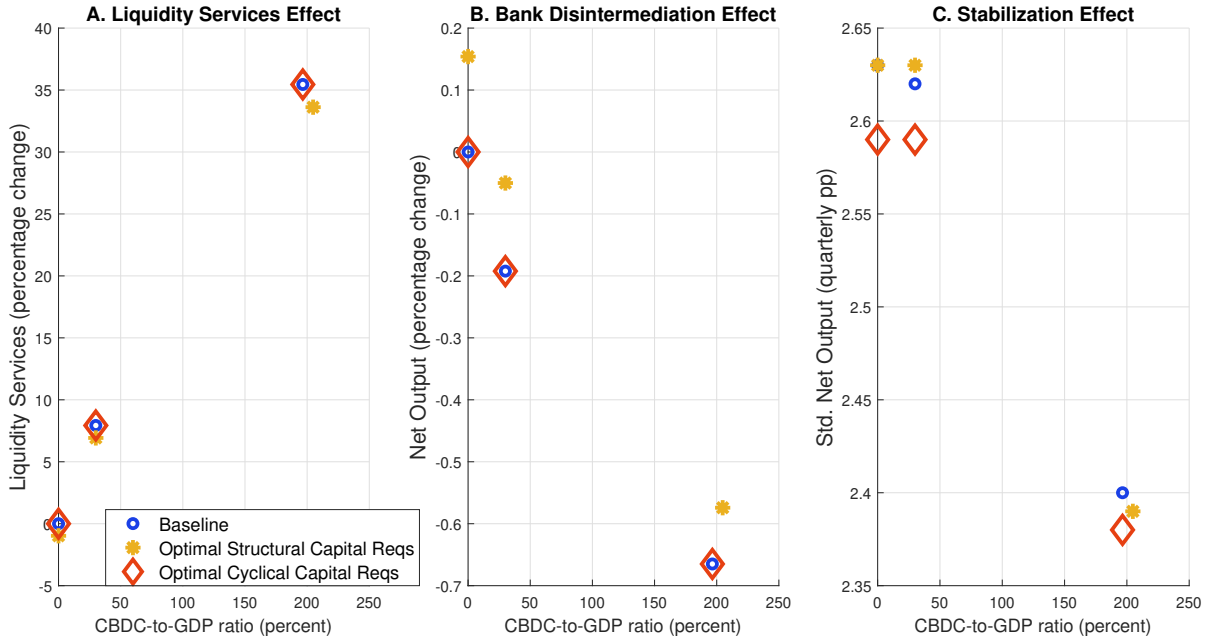
5.4 CBDC Effects and Optimal Bank Capital Regulation

Burlon et al. (2024) show through the lens of a quantitative macro-banking model in which CBDC and deposits are imperfect substitutes and enter the utility function, that the aggregate welfare consequences of CBDC fundamentally follow from three main macroeconomic effects. A liquidity services effect, according to which households benefit from more and better liquidity services. A bank disintermediation effect by which borrowers are adversely affected via credit tightening. A stabilization effect that CBDC induces by smoothing bank deposit funding (and lending) through the liquidity services aggregator.

Figure 10 illustrates how optimal structural capital requirements (yellow asterisk) and optimal

cyclical capital requirements (red diamond) impact each of these three CBDC effects. As shown in Panel A, the level of liquidity services increases with the amount of CBDC in circulation, and the magnitude of such effect is roughly unaffected by optimal capital regulation. In contrast, Panel B reveals that the bank disintermediation effect (proxied by the adverse impact on net output) is materially mitigated by optimal structural capital regulation via a reduction in bank riskiness that encourages banks to extend more loans. In particular, raising γ to its optimal level under regime C causes the CBDC-induced adverse impact on net output to fall from 0.2% to less than 0.05%. Furthermore, if the quantity of CBDC is not "very large" (e.g., regimes A and C) optimal cyclical capital regulation strengthens the stabilization effect of CBDC as it lowers the aggregate volatility of the economy, proxied by the standard deviation of net output (Panel C).

Figure 10: CBDC effects & optimal capital requirements



Notes: The figure reports the percentage change in the second-order approximation to the stochastic mean of liquidity services (panel A), the stochastic mean of quarterly net output (panel B), and the stochastic standard deviation of net output (panel C) arising when the economy moves from the baseline (no CBDC) scenario) to each of the three CBDC regimes. The circle, the asterisk and the diamond refer to the baseline calibration capital requirement scenario, the optimal structural capital requirement scenario and the optimal cyclical capital requirement scenario, respectively.

6 Conclusion

There is a burgeoning literature on the effects of CBDC on bank intermediation and the macroeconomy. In the absence of data on central bank digital currencies, this literature is predominantly

theoretical. Moreover, it often omits bank risk; a channel through which CBDC can alter bank profitability and intermediation. This paper provides evidence that, depending on individual bank's capitalization, perceived bank riskiness and optimal capital needs moderately increase in response to digital euro news.

We build and use a quantitative macro-banking model that replicates such evidence. Any CBDC-induced effect on bank riskiness, optimal capital needs and real economic activity can be mitigated by calibrating a limit on individual CBDC holdings. Optimal structural (steady-state) capital requirements contribute to weakening the bank disintermediation effect triggered by CBDC. Optimal cyclical capital regulation strengthen the stabilization effect caused by the introduction of a central bank digital currency.

Our analysis abstracts from regulations other than bank capital requirements that are also relevant to assess the design of central bank digital currencies. On the empirical front, some of the related fruitful avenues for future research include the study of the estimated CBDC effects on bank liquidity needs and (central bank funding-related) collateral needs. On the theoretical front, how CBDC impacts the optimal level of other relevant regulations (e.g., optimal liquidity regulation, optimal central bank collateral requirements, optimal deposit insurance) also constitute promising avenues for future research.

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A Additional Empirical Evidence

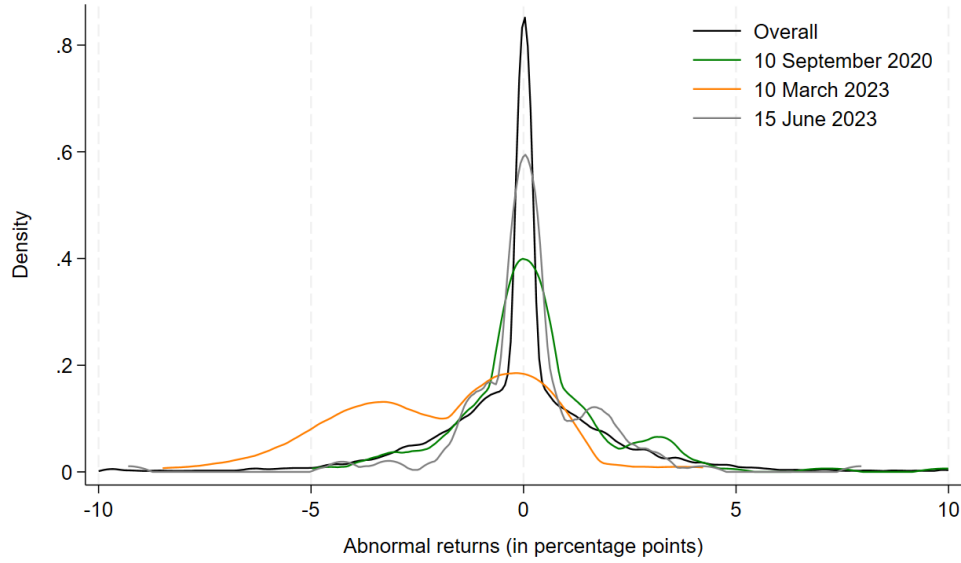
A.1 Tables and Figures

Table A.1: List of digital euro events

Date	Event	Subject	Type of event	Used	GovC
08-Jan-20	INTERVIEW	Christine Lagarde	Interview with “Challenges” magazine	Yes	No
11-May-20	SPEECH	Yves Mersch	An ECB digital currency – a flight of fancy?	Yes	No
07-Jul-20	SPEECH	Fabio Panetta	Unleashing the euro’s untapped potential at global level	Yes	No
10-Sep-20	SPEECH	Christine Lagarde	Payments in a digital world	No	Yes
23-Sep-20	INTERVIEW	Yves Mersch	Interview with Bloomberg	Yes	No
24-Sep-20	INTERVIEW	Philip Lane	Q&A on Twitter	Yes	No
02-Oct-20	THE ECB BLOG	Fabio Panetta	We must be prepared to issue a digital euro	Yes	No
02-Oct-20	PRESS RELEASE	ECB	ECB intensifies its work on a digital euro	Yes	No
05-Oct-20	VOXEU COLUMN	Panetta & Bindseil	CBDC remuneration in a world with low or negative nominal interest rates	Yes	No
12-Oct-20	SPEECH	Fabio Panetta	A digital euro for the digital era	Yes	No
19-Oct-20	INTERVIEW	Christine Lagarde	Interview with Le Monde	Yes	No
22-Oct-20	SPEECH	Fabio Panetta	On the edge of a new frontier: European payments in the digital age	Yes	No
04-Nov-20	SPEECH	Fabio Panetta	The two sides of the (stable)coin	Yes	No
27-Nov-20	SPEECH	Fabio Panetta	From the payments revolution to the reinvention of money	Yes	No
30-Nov-20	INTERVIEW	Christine Lagarde	The future of money – innovating while retaining trust	Yes	No
02-Dec-20	THE ECB BLOG	Fabio Panetta	Money in the digital era	Yes	No
31-Jan-21	INTERVIEW	Isabel Schnabel	Interview with Deutschlandfunk	Yes	No
09-Feb-21	INTERVIEW	Fabio Panetta	Interview with Der Spiegel	Yes	No
10-Feb-21	SPEECH	Fabio Panetta	Evolution or revolution? The impact of a digital euro on the financial system	Yes	No
25-Feb-21	INTERVIEW	Isabel Schnabel	Interview with LETA	Yes	No
02-Mar-21	INTERVIEW	Luis de Guindos	Interview with Público	Yes	No
17-Mar-21	INTERVIEW	Frank Elderson	Q&A on Twitter	Yes	No
25-Mar-21	THE ECB BLOG	Fabio Panetta	Digital central bank money for Europeans – getting ready for the future	Yes	No
08-Apr-21	SPEECH	Christine Lagarde	IMFC Statement	Yes	No
09-Apr-21	INTERVIEW	Isabel Schnabel	Interview with Der Spiegel	Yes	No
11-Apr-21	INTERVIEW	Fabio Panetta	Interview with El País	Yes	No
14-Apr-21	PRESS RELEASE	ECB	ECXBpublishes the results of the public consultation on a digital euro	Yes	No
14-Apr-21	SPEECH	Fabio Panetta	A digital euro to meet the expectations of Europeans	Yes	No
03-May-21	INTERVIEW	Luis de Guindos	Interview with La Repubblica	Yes	No
26-May-21	INTERVIEW	Fabio Panetta	Interview with Nikkei	Yes	No
20-Jun-21	INTERVIEW	Fabio Panetta	Interview with Financial Times	Yes	No
14-Jul-21	PRESS RELEASE	ECB	Eurosystem launches digital euro project	Yes	No
14-Jul-21	ECB BLOG	Fabio Panetta	Preparing for the euro’s digital future	Yes	No
29-Jul-21	INTERVIEW	Fabio Panetta	Interview with Corriere della Sera	Yes	No
29-Jul-21	INTERVIEW	Luis de Guindos	Interview with Handelsblatt	Yes	No
16-Sep-21	INTERVIEW	Christine Lagarde	Interview with Bloomberg	Yes	No
19-Oct-21	SPEECH	Fabio Panetta	“Hic sunt leones” – open research questions on the international dimension of central bank digital currencies	Yes	No
25-Oct-21	PRESS RELEASE	ECB	ECB announces members of Digital Euro Market Advisory Group	Yes	No
05-Nov-21	SPEECH	Fabio Panetta	Central bank digital currencies: a monetary anchor for digital innovation	Yes	No
09-Nov-21	SPEECH	Fabio Panetta	Digital currencies around the world – what are the policy implications?	Yes	No
18-Nov-21	SPEECH	Fabio Panetta	Designing a digital euro for the retail payments landscape of tomorrow	Yes	No
19-Nov-21	ECB BLOG	Fabio Panetta	The ECB’s case for central bank digital currencies	Yes	No
10-Dec-21	SPEECH	Fabio Panetta	The present and future of money in the digital age	Yes	No
14-Jan-22	SPEECH	Christine Lagarde	Conference of Parliamentary Committees for Union Affairs (COSAC)	Yes	No
11-Feb-22	INTERVIEW	Christine Lagarde	Interview with Redaktionsnetzwerk Deutschland	Yes	No
14-Feb-22	SPEECH	Christine Lagarde	20th anniversary of the entry into circulation of euro banknotes and coins	Yes	No
18-Feb-22	SPEECH	Fabio Panetta	Central bank digital currencies: defining the problems, designing the solutions	Yes	No
30-Mar-22	SPEECH	Fabio Panetta	A digital euro that serves the needs of the public: striking the right balance	Yes	No
30-Mar-22	PRESS RELEASE	ECB	ECB publishes report on payment preferences as part of digital euro investigation phase	Yes	No
05-May-22	SPEECH	Fabio Panetta	Interview with La Stampa	Yes	No
16-Jan-22	SPEECH	Fabio Panetta	Public money for the digital era: towards a digital euro	Yes	No
15-Jun-22	SPEECH	Fabio Panetta	The digital euro and the evolution of the financial system	Yes	No
16-Jun-22	SPEECH	Fabio Panetta	Bringing European payments to the next stage: a public-private endeavour	Yes	No
13-Jul-22	ECB BLOG	Lagarde & Panetta	Key objectives of the digital euro	Yes	No
26-Sep-22	SPEECH	Fabio Panetta	Demystifying wholesale central bank digital currency	Yes	No
19-Sep-22	SPEECH	Fabio Panetta	Building on our strengths: the role of the public and private sectors in the digital euro ecosystem	Yes	No
17-Oct-22	INVESTIGATION	ECB	Digital euro - our future money (Presentation at Sibos 2022)	Yes	No
07-Nov-22	SPEECH	Christine Lagarde	Digital euro: a common European project	Yes	No
09-Nov-22	INVESTIGATION	ECB	7th Digital Euro MAG meeting - agenda	Yes	No
10-Nov-22	INVESTIGATION	ECB	4th ERPB technical session on digital euro - agenda	Yes	No
06-Dec-22	INVESTIGATION	ECB	5th ERPB technical session on digital euro - agenda	Yes	No
07-Dec-22	LETTER	Fabio Panetta	Letter to Irene Tinagli, ECON Chair, on the technical onboarding package for digital euro prototyping	Yes	No
08-Dec-22	INVESTIGATION	ECB	8th Digital Euro MAG meeting - agenda	Yes	No
16-Jan-23	MEETING	Eurogroup	Eurogroup meeting - digital euro stocktake	Yes	No
23-Jan-23	SPEECH	Fabio Panetta	The digital euro: our money wherever, whenever we need it	Yes	No
24-Jan-23	INTERVIEW	Fabio Panetta	Interview with Handelsblatt	Yes	No
16-Feb-23	INTERVIEW	Isabel Schnabel	Q&A on Twitter	Yes	No
15-Feb-23	SPEECH	Christine Lagarde	European Parliament plenary debate on the ECB Annual Report	Yes	No
10-Mar-23	SPEECH	Fabio Panetta	Digital euro – a work in progress	No	No
24-Apr-23	PRESS RELEASE	ECB	ECB publishes progress report on digital euro and study on possible features of a digital wallet	Yes	No
24-Apr-23	SPEECH	Fabio Panetta	A digital euro: widely available and easy to use	Yes	No
27-Apr-23	SPEECH	Fabio Panetta	Digital euro – a work in progress	Yes	No
17-May-23	SPEECH	Fabio Panetta	Digital euro - for everyone, everywhere in the euro area	Yes	No
15-Jun-23	SOURCED STORY	Euractiv	LEAK: EU Commission wants digital euro accessible to everyone	No	Yes
23-Jun-23	SPEECH	Fabio Panetta	Paradise lost? How crypto failed to deliver on its promises and what to do about it	Yes	No
28-Jun-23	PRESS RELEASE	ECB	ECB welcomes European Commission legislative proposals on digital euro and cash	Yes	No
04-Sep-23	SPEECH	Fabio Panetta	Shaping Europe’s digital future: the path towards a digital euro	Yes	No
13-Oct-23	LEGAL OPINION	ECB	Opinion of the ECB on a proposal for a regulation on the legal tender of euro banknotes and coins (CON/2023/31)	Yes	No
18-Oct-23	PRESS RELEASE	ECB	Eurosystem proceeds to next phase of digital euro project	Yes	No
17-Nov-23	SPEECH	Piero Cipollone	The digital euro: a digital form of cash	Yes	No
20-Dec-23	PUBLICATION	EBF	Copenhagen Economics study on the impact of a digital euro on financial stability and consumer welfare	Yes	No
07-Feb-24	SOURCED STORY	POLITICO	POLITICO Pro Morning Financial Services Europe: No carte blanche for ECB over digital euro	Yes	No
09-Feb-24	REPORT	Stefan Berger	Rapporteur and MEP Berger tabled his draft report	Yes	No
14-Feb-24	SPEECH	Piero Cipollone	Preserving people’s freedom to use a public means of payment: insights into the digital euro preparation phase	Yes	No
14-Feb-24	SPEECH	Piero Cipollone	European retail payments in the digital era	Yes	No
13-Mar-24	SPEECH	Piero Cipollone	Digital euro: the future of money	Yes	No
17-Apr-24	SPEECH	Piero Cipollone	Digital euro: the future of money	Yes	No
24-Apr-24	SPEECH	Piero Cipollone	Innovation, integration and independence: taking the Single Euro Payments Area to the next level	Yes	No

Notes: The table reports all the digital euro events considered in the empirical analysis.

Figure A.1: Abnormal stock returns of euro area banks around Digital euro events not included in the sample



Notes: The figure reports the Kernel density of the distribution of abnormal stock market returns $\hat{\gamma}_b^e$ obtained estimating the 3-factor Fama-French model reported in (1). Abnormal returns are computed for each bank b and for each the digital euro event e reported in Table A.1, and are measured in percentage points. The solid black line is the density for the pooled sample. The green, orange and grey lines report the densities for the cross-sectional distribution across banks of the abnormal returns measured on 10 September 2020, 10 March 2023 and 15 June 2023, respectively.

A.2 Empirical Evidence: Relation with tightening period

Table A.2 shows that the reaction of bank capital to CBDC shocks has changed after the start of the tightening period and the related change in interest rate and liquidity environment. A higher interest rate environment is one where the outside option to bank deposits of an unremunerated CBDC is less attractive (average deposit rates in the euro area by the end of our sample had reached 1.4%), thus potentially reducing the sensitivity of bank capital to CBDC shocks. At the same time, a lower liquidity environment (excess liquidity in the euro area decreased by 25% since the start of the tightening period, from €4.3 trillion in end-June 2022 to €3.2 in end-March 2024) is one where the potential absorption of liquidity and the increased precautionary need to maintain higher individual liquidity buffers to withstand the perceived strains brought about by CBDC news are more likely to prompt banks to increase their capital buffers so as to rule out the possibility that temporary future liquidity stress translates into solvency issues, at least in the eyes of bank investors. Thus, whether the tightening period started in July 2022 has contributed positively or negatively to the location of the optimal level of capital in response to CBDC news is an empirical question. Columns (1) to (4) in Table A.2 provide evidence that the reactivity of capital to CBDC

news has increased during the tightening period, especially in the first year after the shocks.²⁰ This evidence suggests that liquidity considerations dominate profitability considerations in the determination of the optimal choice of capital in response to CBDC shocks.

Table A.2: Reaction of bank capital to CBDC shocks during the tightening period

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable: Change in capitalisation	1 quarter ahead	2 quarters ahead	3 quarters ahead	4 quarters ahead	5 quarters ahead	6 quarters ahead
Negative CBDC shock	0.001 (0.005)	0.004 (0.005)	0.010* (0.006)	0.014** (0.006)	0.017** (0.007)	0.019** (0.008)
Negative CBDC shock $\times$ Tightening period	0.007 (0.005)	0.014** (0.006)	0.016** (0.007)	0.018** (0.009)	0.018 (0.013)	0.018 (0.018)
Bank controls	Yes	Yes	Yes	Yes	Yes	Yes
Bank fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,404	1,363	1,321	1,278	1,235	1,192
R-squared	0.173	0.187	0.221	0.245	0.277	0.305

Notes: The table reports the estimated coefficients $\hat{\zeta}^h$ for each quarterly horizon $h = 1, \dots, 6$ in the estimation of model (3). “Tightening period” refers to the quarters from 2022Q3 onwards. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

B Equations of the Model

This section presents the full set of equilibrium equations of the model.

B.1 Households

Households seek to maximize their objective function subject to the following budget constraint:

$$c_{h,t} + q_t(h_{h,t} - h_{h,t-1}) + cbdc_{h,t} + d_{h,t} + b_{h,t} + T_t = R_{t-1}^{cbdc} \frac{cbdc_{h,t-1}}{\pi_t} + \tilde{R}_t^d \frac{d_{h,t-1}}{\pi_t} + R_{t-1}^b \frac{b_{h,t-1}}{\pi_t} + w_t n_{h,t} + \Pi_t, \quad (\text{B.1})$$

where the realized gross return on bank deposits is given by $\tilde{R}_t^d = R_{t-1}^d - (1 - \kappa)\Psi_t$ and $\Pi_t = \Omega_t + J_{r,t}$.

Their choice variables are $c_{h,t}$, $h_{h,t}$, $cbdc_{h,t}$, $d_{h,t}$, $b_{h,t}$ and $n_{h,t}$. The optimality conditions of the problem read

²⁰Given that our sample finishes in 2024Q1, we cannot explore the interaction between CBDC news and the tightening period for horizons beyond those reported. The reduced statistical significance at longer horizon is likely due to the reduced variation available, although the magnitude of the coefficients associated with the interaction remains the same.

$$\lambda_{h,t} = \frac{1}{c_{h,t}}, \quad (\text{B.2})$$

$$q_t \lambda_{h,t} = \frac{\dot{j}_{h,t}}{h_{h,t}} + \beta_h E_t (q_{t+1} \lambda_{h,t+1}), \quad (\text{B.3})$$

$$\lambda_{h,t} = \beta_h E_t (\lambda_{h,t+1} R_t^{cbdc} / \pi_{t+1}) + \frac{\chi z}{z_{h,t}} \left(\frac{z_{h,t}}{cbdc_{h,t}} \right)^{1/\eta}, \quad (\text{B.4})$$

$$\lambda_{h,t} = \beta_h E_t (\lambda_{h,t+1} \tilde{R}_{t+1}^d / \pi_{t+1}) + \frac{\chi z}{z_{h,t}} \left(\frac{z_{h,t}}{d_{h,t}} \right)^{1/\eta}, \quad (\text{B.5})$$

$$\lambda_{h,t} = \beta_h E_t (\lambda_{h,t+1} R_t^b / \pi_{t+1}), \quad (\text{B.6})$$

$$w_t \lambda_{h,t} = n_{h,t}^\phi, \quad (\text{B.7})$$

where the liquidity services aggregator is given by $z_{h,t} (cbdc_{h,t}, d_{h,t}) = \left[cbdc_{h,t}^{(\eta-1)/\eta} + d_{h,t}^{(\eta-1)/\eta} \right]^{\eta/(\eta-1)}$ and $\lambda_{h,t}$ is the Lagrange multiplier on the budget constraint of the representative household.

B.2 Banking Groups

B.2.1 Bankers

The law of motion of bankers' net worth is

$$N_{b,t} = \theta_b \rho_{b,t} \frac{e_{b,t-1}}{\pi_t} + (1 - \theta_b) \chi_b \rho_{b,t} \frac{N_{b,t-1}}{\pi_t}. \quad (\text{B.8})$$

The marginal value of one unit of net worth can be defined as

$$v_{b,t} = E_t \left[\Lambda_{b,t+1} \frac{\rho_{b,t+1}}{\pi_{t+1}} \right], \quad (\text{B.9})$$

where the stochastic discount factor of the banker $\Lambda_{b,t+1}$ is

$$\Lambda_{b,t+1} = \Lambda_{h,t+1} (1 - \theta_b + \theta_b v_{b,t+1}). \quad (\text{B.10})$$

The transfer from retiring bankers to the household net of the initial endowment received by new bankers is given by

$$\Omega_t = (1 - \theta_b) \rho_{b,t} \frac{(e_{b,t-1} - \chi_b N_{b,t-1})}{\pi_t} \quad (\text{B.11})$$

B.2.2 Banks

Banks maximize their objective function subject to a balance sheet identity and a capital requirement constraint,

$$l_{b,t} = e_{b,t} + d_{b,t}, \quad (\text{B.12})$$

$$e_{b,t} \geq \gamma_t l_{b,t}. \quad (\text{B.13})$$

The resulting optimality condition reads

$$E_t \left\{ \Lambda_{b,t+1} \left[(1 - G_{t+1}(\bar{\omega}_{b,t+1})) R_{t+1}^l / \pi_{t+1} - (1 - F_{t+1}(\bar{\omega}_{b,t+1})) (1 - \gamma_t) R_t^d / \pi_{t+1} \right] \right\} = \gamma_t v_{b,t}. \quad (\text{B.14})$$

The threshold for the value of $\omega_{b,t}$ below which the bank defaults is

$$\bar{\omega}_{b,t+1} = (1 - \gamma_t) \frac{R_t^d}{R_{t+1}^l}. \quad (\text{B.15})$$

B.3 Entrepreneurs

Entrepreneurs seek to maximize their objective function subject to a budget constraint and the corresponding borrowing limit:

$$c_{e,t} + R_t^l \frac{l_{e,t-1}}{\pi_t} + q_t (h_{e,t} - h_{e,t-1}) = r_t^h h_{e,t-1} + l_{e,t}, \quad (\text{B.16})$$

$$l_{e,t} \leq m_t^h E_t \left[\frac{q_{t+1}}{R_{t+1}^l} h_{e,t} \pi_{t+1} \right], \quad (\text{B.17})$$

Their choice variables are $c_{e,t}$, $l_{e,t}$ and $h_{e,t}$. The following optimality condition can be derived from the first order conditions of the problem

$$\lambda_{e,t} = \frac{1}{c_{e,t}}, \quad (\text{B.18})$$

$$\lambda_{e,t} = \beta_e E_t (\lambda_{e,t+1} R_{t+1}^l / \pi_{t+1}) + \mu_{e,t}, \quad (\text{B.19})$$

$$q_t \lambda_{e,t} = \beta_e E_t [\lambda_{e,t+1} (q_{t+1} + r_{t+1}^h)] + \mu_{e,t} m_t^h E_t \left[\frac{q_{t+1}}{R_{t+1}^l} h_{e,t} \pi_{t+1} \right], \quad (\text{B.20})$$

where $\lambda_{e,t}$ and $\mu_{e,t}$ are the Lagrange multipliers on the budget constraint and the borrowing limit of the representative entrepreneur, respectively.

B.4 Intermediate Goods Producers

There is a continuum of intermediate good producers. Each intermediate good producer j operates the following Cobb-Douglas production function:

$$Y_{r,t}(j) = A_t h_{r,t-1}(j)^\nu n_{r,t}(j)^{(1-\nu)}, \quad (\text{B.21})$$

Intermediate good producers solve a two-stage problem. In the first stage, they choose the trajectories of $h_{r,t-1}(j)$ and $n_{r,t}(j)$ that minimize total real costs, $r_t^h h_{r,t-1}(j) + w_t n_{r,t}(j)$:

$$\frac{w_t}{r_t^h} = \frac{(1-\nu)}{\nu} \frac{h_{r,t-1}}{n_{r,t}}, \quad (\text{B.22})$$

$$mc_t = \frac{(w_t)^{(1-\nu)} (r_t^h)^\nu}{A_t (1-\nu)^{(1-\nu)} \nu^\nu}. \quad (\text{B.23})$$

The firms that can change prices in period t set them to satisfy:

$$g_t^1 = \lambda_{h,t} mc_t Y_{r,t} + \beta_h \theta E_t \left(\frac{\pi_t^\chi}{\pi_{t+1}} \right)^{-\varepsilon} g_{t+1}^1, \quad (\text{B.24})$$

$$g_t^2 = \lambda_{h,t} \pi_t^* Y_{r,t} + \beta_h \theta E_t \left(\frac{\pi_t^\chi}{\pi_{t+1}} \right)^{1-\varepsilon} \left(\frac{\pi_t^*}{\pi_{t+1}^*} \right) g_{t+1}^2, \quad (\text{B.25})$$

$$\varepsilon g_t^1 = (\varepsilon - 1) g_t^2. \quad (\text{B.26})$$

The price level and price dispersion v_t , respectively, evolve according to:

$$1 = \theta \left(\frac{\pi_{t-1}^\chi}{\pi_t} \right)^{1-\varepsilon} + (1 - \theta) \pi_t^{*1-\varepsilon}, \quad (\text{B.27})$$

and

$$v_t = \theta \left(\frac{\pi_{t-1}^\chi}{\pi_t} \right)^{-\varepsilon} v_{t-1} + (1 - \theta) \pi_t^{*- \varepsilon}, \quad (\text{B.28})$$

where χ refers to the inflation indexation parameter.²¹ Profits from each intermediate good producer j are transferred to households:

$$J_{r,t}(j) = Y_{r,t}(j) - [r_t^h h_{r,t-1}(j) + w_t n_{r,t}(j)]. \quad (\text{B.29})$$

B.5 Final Goods Producers

The representative, perfectly competitive, final goods producer chooses the trajectory of intermediate good $Y_{r,t}(j)$ that maximizes $P_t Y_t - \int_0^1 P_t(j) Y_t(j) dj$, where Y_t denotes final production and P_t is the aggregate price level. $Y_t(j)$ denotes demand for intermediate good j and $P_t(j)$ is the corresponding price. The homogeneous final good is produced by means of a Dixit-Stiglitz technology, $Y_t = \left[\int_0^1 Y_t(j)^{(\varepsilon-1)/\varepsilon} dj \right]^{\varepsilon/(\varepsilon-1)}$, where $\varepsilon > 1$ is the elasticity of substitution across intermediate goods. Profit maximization yields demand functions for intermediate good j : $Y_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\varepsilon} Y_t$, $\forall j$. From the zero profit condition, $P_t Y_t = \int_0^1 P_t(j) Y_t(j) dj$, it follows that P_t can be interpreted as the price index: $P_t \equiv \left[\int_0^1 P_t(j)^{(1-\varepsilon)} dj \right]^{1/(1-\varepsilon)}$.

B.6 Public Authorities

B.6.1 Central Bank

The central bank sets the policy rate (i.e., the interest rate on the risk-free asset) according to a Taylor-type policy rule:

$$r_t^b = \rho_r r_{t-1}^b + (1 - \rho_r) (\bar{r}^b + \alpha_\pi \tilde{\pi}_t + \alpha_Y \tilde{y}_t) + e_t^r. \quad (\text{B.30})$$

²¹For simplicity, in the baseline calibration this parameter is set to a value of 0.

The central bank also issues CBDC according to

$$cbdc_{cb,t} \leq \phi \bar{Y}, \quad (\text{B.31})$$

and does not remunerate CBDC holdings at any point in time or

$$R_t^{cbdc} = 0. \quad (\text{B.32})$$

Central bank net profits evolve as

$$\Omega_{cb,t} = cbdc_{cb,t} - R_{t-1}^{cbdc} \frac{cbdc_{cb,t-1}}{\pi_t}. \quad (\text{B.33})$$

B.6.2 Prudential Authority

The prudential authority sets the regulatory capital requirement according to a simple rule

$$\gamma_t = \rho_\gamma \gamma_{t-1} + (1 - \rho_\gamma) \left(\gamma + \gamma_x \tilde{X}_t \right) \quad (\text{B.34})$$

B.6.3 Deposit Insurance Scheme

Lump-sum taxes collected by the DIS are given by

$$T_t = \kappa \Psi_t \frac{d_{h,t-1}}{\pi_t} - \Omega_{cb,t}, \quad (\text{B.35})$$

where total losses incurred by households on deposits that are not covered with repossessed bank assets are given by

$$\Psi_t \frac{d_{h,t-1}}{\pi_t} = \left[(R_{t-1}^d d_{b,t-1}) \frac{F(\bar{\omega}_{b,t})}{\pi_t} - (1 - \mu_b) R_t^l l_{b,t-1} \frac{G_t(\bar{\omega}_{b,t})}{\pi_t} \right]. \quad (\text{B.36})$$

$F(\bar{\omega}_{b,t})$ is the probability of bank default

$$F(\bar{\omega}_{b,t}) = \int_0^{\bar{\omega}_{b,t}} f(\omega_b; \sigma_{\omega,t}) d\omega_b = F \left[\frac{\log(\bar{\omega}_{b,t}) + \sigma_{\omega,t}^2/2}{\sigma_{\omega,t}} \right], \quad (\text{B.37})$$

and $G(\bar{\omega}_{b,t})$ is the share of total assets owned by bankers which end up in default

$$G(\bar{\omega}_{b,t}) = \int_0^{\bar{\omega}_{b,t}} \omega_b f(\omega_b; \sigma_{\omega,t}) d\omega_b = F \left[\frac{\log(\bar{\omega}_{b,t}) - \sigma_{\omega,t}^2/2}{\sigma_{\omega,t}} \right], \quad (\text{B.38})$$

with $f(\omega_b; \sigma_{\omega,t})$ and $F[\cdot]$ denoting the probability density function and the cumulative distribution function of the bank-idiosyncratic asset return shock $\omega_{b,t}$, respectively. This shock is i.i.d. across banks and follows a log-normal distribution with a mean of one and a standard deviation, $\sigma_{\omega,t} = \sigma_{\omega} \varepsilon_t^{\omega}$, that evolves stochastically over time, driven by some aggregate risk shocks ε_t^{ω} .

B.7 Aggregation and Market Clearing

Market clearing is implied by the Walras' law, by aggregating all the budget constraints. The aggregate resource constraint of the economy represents the equilibrium condition for the final goods market:

$$Y_t = C_t + \mu_b R_t^l l_{b,t-1} \frac{G_t(\bar{\omega}_{b,t})}{\pi_t}. \quad (\text{B.39})$$

Similarly, in equilibrium labor demand equals total labor supply,

$$n_{r,t} = n_{h,t}. \quad (\text{B.40})$$

The stock of real estate must equal the demand coming from households and entrepreneurs

$$\bar{H} = h_{h,t} + h_{e,t}. \quad (\text{B.41})$$

Aggregate net worth of bankers equals equity issued by banks

$$N_{b,t} = e_{b,t}. \quad (\text{B.42})$$

Similarly, in equilibrium demand for loans of entrepreneurs equals bank credit supply

$$l_{e,t} = l_{b,t}. \quad (\text{B.43})$$

The stock of bank deposits held by households must be equal to banks' deposit funding

$$d_{h,t} = d_{b,t}. \quad (\text{B.44})$$

CBDC issued by the central bank equals demand for this monetary instrument

$$cbdc_{cb,t} = cbdc_{h,t}. \quad (\text{B.45})$$

In equilibrium, the risk-free asset is in zero net supply

$$b_t = 0. \quad (\text{B.46})$$

B.8 Shocks

The following zero-mean, AR(1) shocks are present in the baseline calibration model: A_t , ε_t^h , ε_t^m , ε_t^σ . These shocks follow the processes given by:

$$\log A_t = \rho_A \log A_{t-1} + e_t^A, \quad e_t^A \sim N(0, \sigma_A). \quad (\text{B.47})$$

$$\log \varepsilon_t^h = \rho_h \log \varepsilon_{t-1}^h + e_t^h, \quad e_t^h \sim N(0, \sigma_h), \quad (\text{B.48})$$

$$\log \varepsilon_t^m = \rho_m \log \varepsilon_{t-1}^m + e_t^m, \quad e_t^m \sim N(0, \sigma_m), \quad (\text{B.49})$$

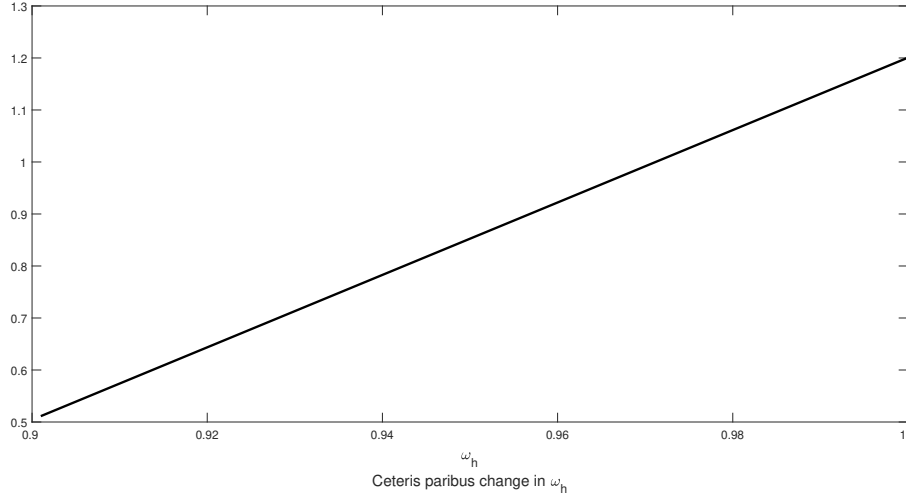
$$\log \varepsilon_t^\omega = \rho_\omega \log \varepsilon_{t-1}^\omega + e_t^\omega, \quad e_t^\omega \sim N(0, \sigma_\omega). \quad (\text{B.50})$$

For the purpose of illustrating the implications of optimal capital requirements for the transmission of CBDC, the model also allows for zero-mean, AR(1) CBDC supply shocks, ε_t^ϕ , which follow the process given by:

$$\log \varepsilon_t^\phi = \rho_\phi \log \varepsilon_{t-1}^\phi + e_t^\phi, \quad e_t^\phi \sim N(0, \sigma_\phi). \quad (\text{B.51})$$

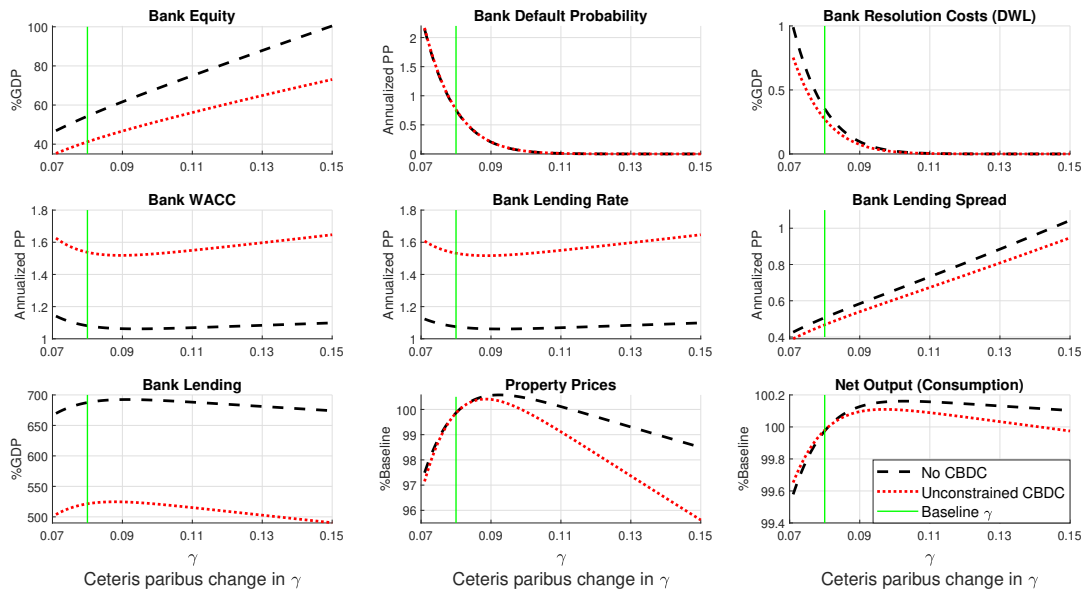
C Quantitative Analysis

Figure C.1: Social welfare gains of optimal capital requirements and CBDC with holding limit (ceteris paribus changes in ω_h)



Notes: Second-order approximation to the unconditional social welfare gains (expressed in percentage permanent consumption) as a function of the utility weight of households, ω_h , under regime C (CBDC with holding limit) with optimal capital requirements (γ^* ; γ_x^* ; ρ_γ^*).

Figure C.2: Transmission mechanisms and steady state effects of structural capital requirements



Notes: Effects on the steady state level of selected variables from ceteris paribus changes in capital requirement parameter, γ . Each variable is expressed as a percentage of quarterly real GDP (proxied by net output), as annualized percentage points or as a percentage of its baseline calibration level.