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THE OPTIMAL QUANTITY OF CBDC IN A BANK-BASED ECONOMY

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The optimal quantity of CBDC in a bank-based economy*

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Abstract

We provide evidence on the estimated effects of news about the introduction of a digital euro on bank valuations and lending and find that the effects depend on the reliance on deposit funding and design features aimed at calibrating the quantity of the central bank digital currency (CBDC). Then, we develop a quantitative DSGE model that replicates such evidence and incorporates key selected mechanisms through which CBDC issuance could affect bank intermediation and the economy. Under empirically-relevant assumptions (i.e. imperfect substitutability across CBDC, cash and deposits and a number of financial constraints such as a collateral requirement for central bank funding), the issuance of CBDC yields non-trivial welfare trade-offs between, on one side, the positive expansion of liquidity services and the improved stabilization of deposit funding and lending and, on the other side, a negative bank disintermediation effect. Welfare-maximizing CBDC policy rules are effective in mitigating the risk of bank disintermediation and induce significant welfare gains. The optimal amount of CBDC in circulation for the case of the euro area lies between 15% and 45% of quarterly GDP in equilibrium. (JEL E42, E58, G21)

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1 Introduction

In recent years, the demand for digital means of payment for retail purposes has steadily increased while the use of cash for transactions has gradually declined (Auer et al. 2020). In response to this shift in payment technologies and preferences, central banks all over the world have started to investigate the potential benefits and implications of issuing central bank digital currencies (CBDCs). The ultimate goal of introducing a CBDC is to ensure that individuals operating in an increasingly digitalized economy keep having access to the safest form of money, central bank money. Among the many potential benefits CBDCs entail, satisfying the demand for a safe, digital means of payment stands out. The most discussed challenge of issuing a CBDC is the risk of bank disintermediation as households substitute bank deposits for CBDC, thereby reducing a relatively cheap funding source for banks.

Against this background, the current debate focuses on how to calibrate the amount of CBDC in circulation so as to ensure that potential benefits of CBDC materialize without harming monetary and financial stability through bank disintermediation. One challenge in this regard is that advanced economies have no experience with CBDCs and, hence, there is no available data on which empirical analysis can be performed. For this reason, the literature has focused on studying the implications of CBDCs based on theoretical models which can be grouped into three main categories: (i) models of payments and modern monetarist models in the spirit of Lagos and Wright (2005), useful to explore design choices of a CBDC as a means of payment; (ii) banking models in the tradition of Diamond and Dybvig (1983), relevant to study the potential implications of CBDC for the severity of bank runs; and (iii) quantitative DSGE models, important to evaluate the general equilibrium and macroeconomic effects of issuing CBDCs.

This paper falls in the third group. Its main contributions are threefold. First, we provide empirical evidence on the impact of digital euro-related news on bank stock prices and lending behavior in the euro area. Second, we develop and calibrate a quantitative euro area DSGE model that accounts for such evidence and incorporates a selection of key transmission mechanisms through which CBDC can affect banks and the real economy. Finally, we analyze a variety of welfare maximizing CBDC policy rules. Such exercise allows us to give a sensible range of values for the optimal amount of CBDC in circulation.

The response of bank stock prices to news about the digital euro project provides insights as to what market participants expect the effect of a digital euro on bank profitability to be. In section 2, we isolate, by means of Fama-French factors, the abnormal returns on euro area banks' stocks around events related to digital euro news, and look at which bank characteristics correlate with these returns. Moreover, we check whether bank credit supply was affected by exposure to these events. We find that the stock prices of banks that rely more heavily on deposit funding are negatively affected. Moreover, this sensitivity leads to a significant drop in lending. At the same time, we show that these effects disappear following news on the design features of the digital euro aimed at calibrating the amount of central bank digital currency in circulation. Our findings suggest that market participants perceive that a certain degree of substitutability between deposits and CBDC may hurt banks that rely on relatively cheap deposit funding unless the amount of CBDC is constrained.

In section 3, we develop a quantitative DSGE model with a banking sector calibrated to the euro area economy. We model a monetary economy populated by two types of households: patient households who are net savers and hold a variety of financial and monetary instruments, three of which provide them with liquidity services (i.e., bank deposits, cash and CBDC); and impatient households, who borrow funds from banks against housing collateral (Iacoviello 2005).[1] Patient households own all firms operating in the economy: capital and final goods producing firms, entrepreneurial firms, and banks. Each entrepreneurial firm is run by a manager, who obtains bank lending against eligible collateral (Kiyotaki and Moore 1997), and a retailer (intermediate good producer) who operates under monopolistic competition in the market of her own variety and sets prices a la Calvo (1983). Banks intermediate funds by borrowing from patient households (in the form of one-period deposits) and lending to impatient households and entrepreneurs (in the form of one-period loans). Bank assets (i.e., loans, government bonds and reserves) are funded by equity, deposits and central bank borrowing. Banks operate subject to a capital adequacy constraint (Iacoviello 2015) and a liquidity (reserves) requirement (Brunnermeier and Koby 2018), and obtain complementary funding from the central bank against eligible collateral (government bonds). All borrowing and regulatory constraints are binding in a neighborhood of the steady state.

The model is completed with a policy block. Government spending is a constant fraction of steady-state real output. The government finances its deficit by issuing one-period government bonds. Tax revenues, collected in a lump-sum fashion from households, are adjusted in response to changes in the holdings of government debt by banks and patient households. The central bank sets the lending facility rate according to a simple Taylor-type rule and the interest rate on reserves so as to maintain a constant corridor between these two policy rates. Central bank assets (i.e., loans to private banks) are financed by issuing reserves, banknotes and CBDC and central bank profits are transferred to the government. CBDC supply is set by means of a simple quantity or interest rate policy rule.

Then, we calibrate the model to quarterly data of the euro area for the period 2000:I - 2021:II,

[1] The 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.

and match a number of first and second moments of banking and macroeconomic aggregates. The model captures the main transmission mechanisms of CBDC, which can be summarized in four steps (Figure 1):

Liquidity services expansion: Due to the imperfect substitutability across the three assets that provide liquidity services, the issuance of CBDC only partially replaces cash and bank deposits, and leads to an expansion of aggregate liquidity services. In other words, the increase in CBDC holdings more than compensates for the joint decline in cash and deposits.

Central bank balance sheet expansion: In response to the fall in deposits, banks draw down reserves held at the central bank, but less than proportionally in line with the reserve requirement. As a result, the central bank balance sheet expands. The increase in CBDC is larger than the joint reduction in the two other central bank liabilities, cash and reserves. This balance sheet expansion boosts central bank profits and the seigniorage transferred to the government, due to the combination of a larger balance sheet and higher profitability as the central bank's liabilities partially shift from costly reserves to zero or negative interest bearing CBDC. It also implies that banks obtain additional central bank funding against eligible collateral (i.e., government bonds).[2]

Bank disintermediation: The substitution of relatively cheap deposit funding for more costly central bank borrowing increases the overall funding cost of banks. Moreover, on the asset side, the share of government bonds increases at the expense of lending to the private sector which is comparatively more profitable due to the increased collateral requirements for central bank borrowing. Overall, this triggers a compression in bank net interest margins. Such adverse impact on bank profitability exerts a downward pressure on bank equity (which accumulates out of retained earnings) and a deleveraging which is fully borne by lending to the private sector since the risk weight of reserves and government bonds is equal to zero. The tightening in credit supply adversely affects real economic activity.

Fiscal expansion: The central bank balance sheet expansion unambiguously leads to an increase in seigniorage revenues. This relaxes the government budget constraint and allows the government to reduce taxes or increase lumpsum transfers, thereby boosting private consumption and mitigating the adverse impact on real GDP caused by bank disintermediation.

In Section 4, we then use the calibrated bank-based DSGE model to analyze the quantitative effects and welfare implications of six different CBDC rules. We compare the results with the baseline case under which there is no CBDC. We consider both quantity and interest rate rules and differentiate between static and dynamic rules. The optimal CBDC policy rule is obtained by

[2]Note that central bank assets take the form of credit to banks, which can benefit from such financing by pledging eligible assets (i.e., government bonds, in the baseline model) as collateral.

maximizing a measure of social welfare - defined as a weighted average of the expected lifetime utility of the two types of households - with respect to the relevant policy parameter vector.[3]

CBDC-induced welfare implications and trade-offs are fundamentally driven by three main effects: a liquidity services effect, a bank disintermediation effect, and a stabilization effect. The first effect has a positive welfare impact on savers as the issuance of CBDC allows savers to enjoy more and better liquidity services. The second effect has a negative welfare impact on the borrowers, as it tightens the availability of credit. These effects have already been thoroughly studied in the literature and the main workings behind them for the case of this model economy have already been outlined earlier in this introduction. The third effect, the stabilization effect, has been less explored in this strand of the literature. The issuance of CBDC stabilizes holdings of the two other monetary instruments (including deposits) - through the liquidity services aggregator - thereby exerting a smoothing effect on bank lending that positively affects borrowers' welfare. This stabilization effect increases with the amount of CBDC in circulation and the degree of countercyclical responsiveness of the CBDC policy rule.

Overall, the main findings of the paper can be summarized as follows. First, our empirical findings show that calibrating the amount of CBDC in circulation is important to mitigate the impact on the banking sector. Such impact crucially depends on the substitutability between CBDC and deposits and on banks' reliance on deposit funding. Second, our quantitative DSGE analysis permits to distill the different key channels through which a CBDC issuance transmits to the economy. In essence, the imperfect substitutability across monetary instruments implies that introducing a CBDC triggers a liquidity services and a central bank balance sheet expansion. The latter yields a fiscal expansion and a degree of bank disintermediation, with opposing effects on real GDP. Third, welfare-maximizing CBDC rules balance the risk of bank disintermediation with the positive impact of expanded liquidity services and a better stabilization of credit provision. Fourth, the optimal amount of CBDC in circulation for the case of the euro area lies between 15% and 45% of quarterly GDP in equilibrium. For this range of values, the equilibrium interest rate on CBDC is negative and the steady state impact of CBDC on bank valuations and lending is moderate. In contrast, if the effective demand for CBDC that would prevail at a zero interest rate were to be fully satisfied (i.e., unconstrained CBDC supply scenario), the amount of CBDC in circulation would be around 65% of quarterly GDP and the steady state effects on bank valuations and lending would be more sizable.

Related Literature This paper contributes to a recent and rapidly growing literature that studies the macroeconomic consequences of issuing CBDCs. Much of this literature focuses on the

[3] Since patient households own all financial and non-financial firms in the economy, the welfare analysis can be restricted to (patient and impatient) households without neglecting any consumption capacity generated in the economy.

trade-off between the potential benefits of CBDC as a safe and innovative means of payment and the risk of bank disintermediation through deposit substitution (see, e.g., Agur et al. 2022; Keister and Sanches 2022).[4] While this literature is already too large for being surveyed here, it offers several conclusions which are worth being highlighted in this paper.[5] First, the seminal work by Barrdear and Kumhof (2022) shows how a CBDC issued against government bonds can permanently raise GDP, even if it partially disintermediates banks, due to a fiscal expansion associated with the increased leverage. This is the first paper that studies the macroeconomic effects of CBDC in a DSGE model and, perhaps, our closest antecedent. While our model captures transmission mechanisms that are already embedded in their DSGE model (imperfect substitutability between CBDC and deposits, fiscal expansion, and bank disintermediation), it includes additional channels which are key in calibrating the transmission of CBDC macroeconomic effects. For example, our model underscores how the impact of CBDC on bank intermediation and the real economy crucially depends on the design of the collateral framework. This is important to provide a reasonable range of values for the optimal quantity of CBDC in our welfare analysis.

Second, a number of recent papers (Andolfatto 2021; Chiu et al. 2019) show that, under certain conditions, the issuance of a CBDC can actually promote bank intermediation and real economic activity structurally. The assumption of imperfect competition in the banking sector is typically behind this result. In our model, banks are assumed to be price takers in the market for deposits.

Third, Brunnermeier and Niepelt 2019 and Fernández-Villaverde et al. 2021 show that, under certain conditions, there are no allocative and macroeconomic consequences of CBDC-induced bank disintermediation as society is implicitly indifferent between obtaining lending through bank deposit funding or via central bank financing .[6] In general, the underlying reason behind the violation of this equivalence result is the presence of a market imperfection. Among others, these frictions may include borrowing constraints (Assenmacher et al. 2021), incomplete information (Muñoz and Soons 2023), or market power (as already mentioned). Interestingly, some papers define the specific conditions under which the equivalence result holds (or can be restored) even with frictions such as imperfect competition in the banking sector (Niepelt 2022) or banks' borrowing limits (Abad et al. 2023). In our model, we introduce various financial frictions such as a liquidity requirement, a capital constraint and a collateral constraint, which naturally lead to a breach of the equivalence result.

[4] Schilling et al. (2020) propose a different but very interesting conflict (in terms of attainable policy objectives) introduced by CBDC. Their CBDC trilemma states that a central bank that issues a CBDC can never deliver more than two out of the three following objectives at the same time: price stability, financial stability, and allocative efficiency.

[5] For recent reviews of the literature on CBDC, see Ahnert et al. (2022) and Infante et al. (2022).

[6] For a discussion on the conditions that would need to hold for this equivalence result to apply in practice, see Niepelt (2020).

Fourth, there are different channels through which the introduction of a CBDC can be costly to banks and translate into a tightening in bank lending conditions. In Piazzesi and Schneider (2022), the complementarities between credit line provision and deposits is undermined by the partial replacement of the latter with CBDC, which forces banks to hold excessive volumes of costly assets. In our model, it is the fact that central bank financing is more costly than deposit funding (also due to the collateral requirement) which reduces bank profitability and lending. In contrast, if excess reserves are sufficiently large, reserves and deposits are remunerated at the same rate (in a floor system), and there is no central bank collateral requirement, Abad et al. (2023) show that a central bank balance sheet expansion induced by the imperfect substitutability across monetary instruments can be neutral for bank intermediation and the macroeconomy. Other papers underscore the importance of the international dimension to assess the impact of CBDCs on banks and the macroeconomy (Bacchetta and Perazzi 2021; Ferrari Minesso et al. 2022; Kumhof et al. 2023).

Fifth, beyond that of providing liquidity services with a safe and innovative instrument, CBDC can entail other benefits from a macroeconomic and financial stability perspective. For instance, Williamson (2022b) shows that bank runs are less disruptive with CBDCs, Keister and Monnet (2022) argue that a CBDC enhances the central bank monitoring of the financial system, and Williamson (2022a) defends that CBDC favours a more efficient use of safe collateral. Barrdear and Kumhof (2022) and Schiller and Gross (2021) provide some insights into how a CBDC can contribute to stabilizing the banking sector and the economy. [7]

The paper is organized as follows. Section 2 presents novel empirical evidence on the estimated impact of digital euro news on euro area banks' stock prices and lending. Section 3 describes the macro-banking DSGE model calibrated to the euro area economy and the transmission mechanisms of issuing CBDC. Section 4 develops a quantitative exercise to assess the effects of welfare-maximizing CBDC rules under different policy regimes. Section 5 concludes.

2 Empirical Evidence

The response of bank stock prices to news about the possible introduction of a digital euro may provide some insight as to what investors currently think the introduction of a digital euro might entail for banks' business models. In particular, to the extent that banks' stock prices reflect the present discounted value of the future profits, their changes around such news events can be a measure of the perceived impact of the digital euro on bank profitability. In this section, we analyse the response of bank stock prices to digital euro news and its consequences for the euro

[7]For a recent paper that studies the business cycle effects of CBDC in a New Monetarist NK model, see Assenmacher et al. (2023).

area bank lending conditions.

2.1 Stock Market Reactions to Digital Euro News

We run a cross-sectional event study to analyze banks' stock price reactions to news related to the digital euro.[8] Following Sefcik and Thompson (1986), we start by estimating banks' abnormal returns associated with digital euro news using a Fama and French (1993) three-factor model. 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 regularities captured by Fama-French factors. The sample with data from Iboxx is based on 134 banks from 1 January 2007 to 31 May 2021. 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 vs. 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 $e = 1, ..., E$, which take value 1 if the event e takes place in day t.

The series of daily events related to digital euro are distributed over 2020 and 2021. Table A.1 reports the full list of events considered. They all relate to public interventions by ECB board members, and range from official press releases to interviews and speeches, to entries in ECB's official blog and the publication of a VoxEU column. All these events have a precise date of publication, which is used as date to identify the event. In principle, if the days of the digital euro events coincided with monetary policy announcements, this would pose a significant challenge on the interpretability of the daily responses. Fortunately, the digital euro announcements were by design located in windows of time that showed little to no overlap with monetary policy announcements.[9] This was arguably done not to blur the intended monetary policy signals with communications that are not necessarily related to monetary policy in a strict sense. In fact, in the communications and interviews by ECB board members, the digital euro does not appear to be intended as a monetary policy instrument per se, but rather a form of central bank money complementary to physical cash and wholesale central bank deposits, as well as a means to ensure that sovereign money remains

[8] For overviews of the event study methodology, see MacKinlay (1997) and Binder (1998).

[9] In our sample, there was only one day (10 September 2020) when a digital euro event (a speech by ECB President Lagarde) coincided with a monetary policy announcement (the monetary policy decision taken by the Governing Council of the ECB on the same day). These events were associated with negligible bank stock returns as well as no noticeable change in the monetary policy stance.

at the core of European payment systems. We provide an illustration of the sequence of events in Figure A.1 in Appendix A.

Figure 2 reports the results of the analysis. We compute the average cumulated abnormal return up to day t as $1/B \sum_b \sum_{e=1}^{e(t)} \hat{\gamma}_b^e$, where $e(t)$ is the latest event up to day t, B being the total number of banks, and $\hat{\gamma}_b^e$ is the abnormal return of bank b in event e estimated with model (1). The average cumulated abnormal return has remained relatively stable until 2 October 2020, date in which the ECB stated its intention to intensify work on a digital euro by means of a press release. After that date, every additional communication on the subject has led to a marginal negative return on bank stocks, stabilizing between end October 2020 and the early February 2021 at around 1% below the level prevailing since the beginning of 2020. The trend was inverted after ECB Board member Panetta gave an interview on 9 February 2021 followed by a speech on 10 February 2021, when the potential limit on individual holdings of EUR 3,000 was floated again among other aspects. After that date, events were associated with positive or neutral reactions of stock market valuations, ending by May 2021 on average at around 1% above the level at the beginning of 2020.

The aggregate picture hides important heterogeneity in the cross-section. Stocks of banks with different business models have been reacting in a systematically different way to digital euro news. In particular, banks with a ratio of deposits over total liabilities above the median have experienced larger drops in valuations in response to digital euro events, summing up to a cumulated drop of over 2% by end-2020 on average. At the same time, they have also experienced a rebound after 9 February 2021, ending the year at the same valuation that they had in early 2020. This reaction is consistent with market participants either discounting a potentially large disintermediation effect or needing several months to absorb the information flow on this subject. The pattern was different for banks less reliant on deposit funding, which instead experienced an increase in valuations since October 2020, followed by a plateau over 2021. This is in line with the considerations on the potential positive impact on bank profitability, related to the potential new business opportunities created by the digital euro like innovative payment services as well as the levelling of the playing field with the digital payment and financial services offered by global tech giants.[10] The economic significance of these estimated abnormal returns on bank stock prices is sizable. We report the historical correlation of bank stock returns and the subsequent evolution of banks' profits in the euro area in Figure A.2 in Appendix A, both unconditionally and conditionally on other covariates and unobserved heterogeneity. This helps us to map, for example, the 4 percentage points difference between high deposit and low deposit banks in stock returns associated with digital euro news (see Figure 2) into a predicted dispersion in bank ROEs of 0.5 percentage points, which is around half of 2020 average bank ROE in the euro area (which was kept particularly low due to the increase in

[10] See, e.g., Panetta, F., (2020). "Preparing for the euro's digital future." The ECB Blog, 14 July 2021 (Table A.1).

pandemic-related provisioning) and a tenth of the ROE in 2019 or 2021. These elasticities have the same magnitude as the aggregate impact of the digital euro on euro area banks' ROE considered in market analysts' reports published around similar dates of the events, which offer a proxy of the impacts priced in by markets at the time. In these reports, the digital euro was estimated to potentially lower banks' ROE by between 0.2 and 1.5 percentage points.[11]

We also classify the events listed in Table A.1 into three broad categories. Events labelled with 'Fostering D€' suggested an acceleration of the digital euro project and an increase in the likelihood of an eventual adoption of a CBDC in the euro area. Events labelled 'Neutral' reported news and considerations about the digital euro without specific information on the project itself. Events labelled 'Detailing D€' conveyed to the public key information on the design features and timing of a future potential digital euro aimed at limiting the financial risks associated with its adoption.[12] We compute the average stock returns around those events for each type of event and each set of banks, those highly dependent on deposit funding and those less dependent on deposit funding. The results, reported in Figure A.3, show that banks with a high deposit ratio experienced negative returns around events that fostered the adoption of a digital euro, almost nil returns around neutral events, and positive returns around events that limited the scope and pace of a potential future digital euro adoption. Returns for banks with a low deposit ratio were instead on average higher than returns for banks with a high deposit ratio around digital euro events. The abnormal returns on bank stocks with respect to the part of returns explained by the Fama-French factors, which is the measure reported in cumulated terms in Figure 2, show an even more clear-cut distinction between bank groups depending on the type of news. 'Fostering D€' news decrease returns for high deposit banks and increase them for low deposit banks, 'Neutral' news give rise to no abnormal returns, 'Detailing D€' news increase returns only for high deposit banks while leave other banks' stock unaffected.

Table 1 illustrates further that reliance on deposit funding is the variable that most consistently helps to explain abnormal returns around digital euro events. The model estimated is as follows:

$$\hat{\gamma}_b^e = \delta \text{Deposit ratio}_{b,e} + \zeta_e + \zeta_b + X_{b,e} + \varepsilon_{b,e}, \tag{2}$$

where the observation is a given bank b in an event e, $\hat{\gamma}_b^e$ are the abnormal returns estimated with model (1) for each bank b and each event e, and $X_{b,e}$ is a set of (pre-existing) bank characteristics. The fixed effects ζ_e and ζ_b capture event- and bank-specific unobserved heterogeneity in abnormal returns. Deposit ratio$_{b,e}$ is the ratio of deposit from the non-financial private sector over main liabilities registered by the end of the month before event e. The controls $X_{b,e}$ cover several other

[11]See, e.g., "Central Bank Digital Currencies: Digital money for the masses," Autonomous, 18 February 2021, and "Digital euro: the ECB saving Europe again," Mediobanca Securities, 21 March 2021.

[12]The right column of Table A.1 reports the partition of the events into the three categories.

bank characteristics that may in principle contribute in explaining bank stocks' abnormal returns, especially if the estimation strategy of model (1) was not successful in ruling out confounding factors. The controls include a proxy for size like bank assets, the ratio of TLTRO over assets to measure reliance on central bank funding, securities holdings over assets to measure exposure to asset purchases by the central bank, excess liquidity over assets to measure exposure to the negative interest rate policy, ROA to proxy for general profitability, the NPL ratio to measure the quality of the loan portfolio and the sensitivity to potential deterioration in the economic outlook, and the CDS spread to measure markets' assessment of the bank creditworthiness. In the last column we also offer a robustness check based on Fama-French factors for the aggregate European economy instead of those computed using stocks of euro area banks.[13] The results show that one standard deviation of difference in the deposit ratio (18 percentage points) is associated with over 1 percentage point of difference in abnormal return in each event. Overall, these findings suggest that market participants perceive a certain degree of substitutability between bank deposits and CBDC.

These early considerations on the perceived impact of the digital euro on banks' future profitability are subject to some uncertainty. First, it might still be difficult for market participants to gauge the potential relevance that a digital euro might have on banks' business model. Second, the model used to isolate abnormal returns from otherwise normal fluctuations of banks' stock prices, however standard, may be misspecified. Third, the period under consideration for quantifying the abnormal returns might also be special, in light of the chronically low price-to-book ratios over the past 5-10 years and the extraordinary environment that emerged from the pandemic. Fourth, there may be concomitant events that increase the measurement error of single events. The current approach partially addresses these concerns with a long time period spanning since 2007, considering a wide set of events referring to digital euro that should average out the potential misrepresentation of single events, with both positive and negative news in terms of their likely impact on stock market valuations.

The lack of overlap with monetary policy events, which happens by design with announcements related to the digital euro, further helps to interpret abnormal stock returns registered around digital euro events as the market response to these news. However, despite the general robustness of the results, the risk of capturing the response to other news using daily data, especially for the most important events, is potentially non-trivial. Thus, in Figure A.4 in Appendix A we look at the minute-by-minute movements in bank stock prices around the two main events we identify in our analysis, the publication of the report on the digital euro on 2 October 2020 and the publication of ECB Board member Panetta's interview on 9 February 2021. As in Bianchi et al. (2019), we use Bloomberg News to characterize exactly the time-stamp (at a minute-by-minute frequency)

[13] The data for this robustness exercise were retrieved from French's webpage.

when the news related to the two main events hit the markets, and then look at the reaction of bank stock prices in the 10 minutes before and 30 minutes after those events. The results show a strong negative return for the 2 October 2020 event (-1% of the level before the shock) and a positive return for the 9 February 2021 event (+0.2% of the level before the shock) concentrated among banks relying on deposit funding. Thus, minute-by-minute movements in stock prices around key digital euro-related events confirm the impacts of digital euro news observable at a daily frequency.

2.2 Impact on Lending Conditions

The reaction of stock prices may have conveyed information to banks as to the impact that the digital euro project may have on their business model. Moreover, an adverse assessment by market participants as to the prospects of a given bank in a world with a digital euro may have also directly translated into more expensive market-based funding options for that bank. Hence, there may be scope for the stock market developments in late 2020 to have had a bearing on banks' lending conditions in the following months. To understand whether that was the case, we look at the developments in loan markets using transaction level data from AnaCredit (the European credit register).

We perform a diff-in-diff exercise where the continuous treatment is the bank-level exposure to abnormal returns up to end-October 2020 and the dependent variable is the growth in lending volume since October 2020. The sample is constituted by the banks for which we can isolate the abnormal returns in model (1), which have around 1.6 million outstanding credit relations with 1.3 million firms distributed in 14 euro area countries over 2020 and 2021.

Our identification strategy addresses many threats to a causal interpretation of the impact of the measured shocks.

First, concerns related to reverse causality are assuaged by the high-frequency identification at the bank level illustrated in the previous section. This allows us to consider the abnormal returns realised around digital euro events as a sudden deterioration in expected bank profitability that was not previously priced in by markets and that cannot be the reflection of pre-existing plans to expand credit by banks more exposed to the shock. The changes in bank profitability prospects have then translated into a different willingness of banks to extend credit via a standard bank lending channel.

Second, to isolate this shift in credit supply, we need to adequately control for credit demand components over the same period. For this, we make use of the information available at the bank-firm level from AnaCredit, the euro area credit register maintained by the European System of Central Banks. This dataset covers close to the universe of corporate loans in the euro area at a monthly frequency, with harmonized data on individual loans from all Member States for exposures above EUR 25,000. AnaCredit includes a rich set of information on loan-specific characteristics, including the outstanding nominal amount. The data also includes a wide set of borrower attributes such as geographical location and sector of economic activity, allowing us to saturate our models with a battery of firm-level controls. In particular, we consider a collection of fixed effects that span the main dimensions of demand components, that is firm sectoral specialisation, geographical location, and size (so-called industry-location-size (henceforth ILS) fixed effects, see Degryse et al. 2019). We consider 2-digit NACE industries, NUTS 3 geocodes and deciles of firms' total exposures in October 2020. This provides 90,104 industry-location-size clusters. The granularity of these clusters is crucial to capture demand and isolate the reaction of credit supply. Moreover, we provide a specification with firm fixed effects to control for firm-specific unobservable heterogeneity in loan demand, thus relying on the sub-sample of multiple-lender borrowers as in Khwaja and Mian (2008). Hence, we rely on variation stemming from exposure to the shock at the bank level within each firm to achieve identification.

Third, the relative reduction in credit supply could be reflecting the exceptional circumstances of the COVID-19 crisis, and in particular the pandemic-related policy response. Exposure to the extraordinary fiscal support over the pandemic period is mostly captured by our firm-level fixed effects, as fiscal support was mostly directed towards borrowers in the form of public guarantee schemes and moratoria, as well as, implicitly, via wide-ranging furlough schemes. Exposure to monetary policy instruments is pinned down by bank balance sheet data from iBSI (individual Balance Sheet Items statistics), a proprietary database maintained at the ECB. Reliance on TLTROs (outstanding TLTROs over assets) captures each bank's reliance on the funding-for-lending scheme of the ECB which was tailored to address bank funding issues at the onset of the pandemic. Securities holdings (as a share of assets) measure the potential capital gains that banks may have realised as a consequence of quantitative easing programs in the euro area (the pre-existing Asset Purchase Programme which was recalibrated on 12 March 2020 and the new Pandemic Asset Purchase Programme announced on 18 March 2020). Excess liquidity holdings (as a share of assets) represent, together with securities holdings, the overall liquidity of a bank's assets, but also capture a bank's exposure to the negative interest rate policy prevailing at that time, with a deposit facility rate set at -0.5% throughout the sample period. ROA, the NPL ratio, and the CDS spreads, gathered from Bureau van Dijk's Orbis Bank Focus and Datastream, cover the remaining confounding factors that may correlate with bank profitability, bank asset quality, and market assessments of bank riskiness.

We estimate the following model:

$$\Delta^h \log(\text{Volume})_{b,f} = \alpha^h_{i,l,s} + \xi^h \hat{\Gamma}_b^{\text{October 2020}} + X_b + X_f + \varepsilon^h_{b,f}, \tag{3}$$

where $\Delta^h \log(\text{Volume})_{b,f}$ is the percentage change of outstanding amounts of loans between bank b and firm f occurred in the months after October 2020 up to horizon h, $\hat{\Gamma}_b^{\text{October 2020}}$ is our treatment variable defined as the (cumulated) abnormal returns in October 2020, X_b are bank controls and X_f are firm controls, and $\alpha^h_{i,l,s}$ is the ILS fixed effects, which in some specifications we substitute with firm fixed effects α^h_f for robustness. Since our treatment is at the bank level, we control for the spurious correlation in errors introduced in this way by clustering standard errors at the bank level.

In Table 2 we look at changes in loan volumes that occurred in the three months following October 2020, that is, until January 2021. The results show a consistently significant impact across specifications, ranging between 0.1 and 0.4% of ex-ante volumes for each percentage point of additional stock market returns attributable to digital euro news. The impact is also economically meaningful, as one standard deviation in abnormal returns (almost 10 percentage points in our sample) can explain over 7% of the standard deviation of changes in loan volumes (using the coefficient from column 3 as a benchmark). The relation is quite robust to the inclusion of bank-level observables capturing banks' exposure to confounding factors such as monetary policy, and to a high level of saturation of the model.

In Figure 3 we apply the benchmark specification of column 3 to other horizons. The changes in loan volumes in the months leading up to October 2020 show that there was no differential trend in lending before the actual drop in stock returns of October 2020, confirming that our diff-in-diff set-up is adequate to isolate the impact of the shock. Moreover, and consistent with the retrenchment in different patterns of stock market returns due to digital euro news observed since early February 2021, the impact on lending seems to be partially transitory, at least up to the horizon covered in the analysis. The reaction of lending volumes by May 2021 is almost half of the trough reached in January 2021, with progressively widening uncertainty surrounding the coefficient.

3 The Model

Consider a monetary, closed, decentralized and time-discrete economy populated by two types of households. Patient households (net savers) and impatient households (net borrowers). Both of them work, consume and accumulate housing. However, impatient households discount the future more heavily than patient ones (i.e., $\beta_i < \beta_p$) implying that, in the aggregate, patient households are net savers whereas impatient ones are net borrowers. Impatient households obtain funds from banks against housing collateral. Patient households hold a variety of assets, some of which are forms of money that serve as means of payments and provide them with liquidity services (i.e., bank deposits, cash and CBDC). Net savers own all different types of firms operating in the economy, including banks, entrepreneurial firms, capital goods producers and final goods producers. For each type of agent and firm in the economy, there is a continuum of individuals in the $[0,1]$ interval.

Banks intermediate financial resources by borrowing from patient households and the central bank and lending to impatient households and non-financial corporations (i.e., entrepreneurial firms). Financial intermediaries have to comply with certain capital and liquidity (reserve) requirements whose modelling is similar to the one proposed in Iacoviello (2015) and Brunnermeier and Koby (2018), respectively. The borrowing capacity of banks with the central bank is tied to the value of their government bond holdings, which serve as eligible assets within the collateral framework of the monetary authority.[14] For each entrepreneurial firm, there is a manager who obtains bank lending to acquire physical capital and commercial real estate and a retailer who rents such inputs and combines them with labor to produce intermediate goods under monopolistic competition and by setting prices a la Calvo (1983).

The government issues one-period bonds to finance its deficit. Tax revenues respond to changes in government bonds held by patient households and banks whereas government spending is assumed to be a constant fraction of steady state real GDP. The central bank sets two policy rates: the rate that is charged to banks when providing them with funds, which is set according to a simple Taylor-type policy rule, and the rate at which bank reserves are remunerated, which is set to maintain a constant corridor between the two policy rates. The monetary authority issues reserves, cash and CBDC and provides lending to the banking sector. when issuing CBDC, there is a third policy rate associated with the remuneration on holding CBDC.

3.1 Main Features

3.1.1 Patient Households: net savers and CBDC holders

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

$$E_0 \sum_{t=0}^{\infty} \beta_p^t \left\{ \frac{1}{1-\sigma_h} \left[c_{p,t} - \frac{n_{p,t}^{1+\phi}}{(1+\phi)} \right]^{1-\sigma_h} + j_{p,t} \log h_{p,t} + \chi_{z,t} \log z_t \right\}, \tag{4}$$

where $\beta_p \in (0,1)$ is the patient households' subjective discount factor, σ_h stands for the risk parameter, and ϕ refers to the inverse of the Frisch elasticity.[15] $j_{p,t}$ and $\chi_{z,t}$ denote possibly

[14] The modelling of banks augments the one presented in the extended model of Muñoz 2021 by: (i) allowing for government debt and reserve holdings on the asset side of the balance sheet, as well as central bank funding on the liabilities side; (ii) incorporating a liquidity (reserves) requirement and a central bank collateral requirement.

[15] Households are assumed to have GHH preferences in consumption and hours worked (see Greenwood et al. 1988). This type of preferences - under which wealth effects on labor supply are arbitrarily close to zero - has been

time-varying preference parameters for housing and liquidity services, respectively. More precisely, $j_{p,t} = j_p \varepsilon_{h,t}$ is the exogenously time-varying patient households' preference parameter for housing services, where $j_p > 0$ and $\varepsilon_{h,t}$ captures exogenous housing preference shocks. Similarly, $\chi_{z,t} = \chi_z \varepsilon_{z,t}$ is the time-varying preference parameter for liquidity services, where $\chi_z > 0$ and $\varepsilon_{z,t}$ captures exogenous liquidity preference shocks.

Liquidity services are derived from holding cash, m_t, central bank digital currency, $cbdc_t$, and bank deposits, d_t, according to the following CES aggregator:

$$z_t\left(m_t, cbdc_t, d_t\right) = \left[m_t^{(\eta_{z,t}-1)/\eta_{z,t}} + cbdc_t^{(\eta_{z,t}-1)/\eta_{z,t}} + \omega_d d_t^{(\eta_{z,t}-1)/\eta_{z,t}}\right]^{\eta_{z,t}/(\eta_{z,t}-1)}, \tag{5}$$

where ω_d measures the liquidity of bank deposits relative to central bank money (i.e., cash and central bank digital currency), and $\eta_{z,t} = \eta_z \varepsilon_{\eta,t}$ is the possibly time-varying elasticity of substitution across different forms of money.[16] Cash, CBDC and deposits provide liquidity and, thus, are substitutes, implying $\eta_z > 1$.Finally, $\varepsilon_{\eta,t}$ captures exogenous shocks to the elasticity of substitution across forms of money.

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

$$\begin{aligned} &c_{p,t} + q_t(h_{p,t} - h_{p,t-1}) + m_t + f(m_t) + cbdc_t + d_t + b_{p,t} + \omega_T T_t \\ &\qquad = \frac{m_{t-1}}{\pi_t} + R_{cbdc,t-1}\frac{cbdc_{t-1}}{\pi_t} + R_{d,t-1}\frac{d_{t-1}}{\pi_t} + R_{g,t-1}\frac{b_{p,t-1}}{\pi_t} + w_t n_{p,t} + \Omega_t, \end{aligned} \tag{6}$$

where $b_{p,t}$ are government bond holdings, $\omega_T \in [0,1]$ is the fraction of total lump-sum taxes, T_t, paid by this household type and $\Omega_t = \Omega_{e,t} + \Omega_{b,t}$ are dividends obtained from their ownership of non-financial corporations (i.e., entrepreneurial firms) and banks. $\pi_t \equiv P_t/P_{t-1}$ is the gross inflation rate, q_t the real price of housing and w_t the real wage rate. $R_{cbdc,t}$, $R_{d,t}$ and $R_{g,t}$ denote the nominal gross interest rates on CBDC, deposits and government bonds, respectively. The technological superiority of CBDC (relative to cash) is captured by the existence of cash storage costs, $f(m_t)$, with $f_m > 0$ and $f_{mm} > 0$.[17] In particular, we assume that $f(m_t) = \left(\frac{\psi_m}{2} m_t^2\right)$.[18]

extensively used in the business cycle literature as a useful device to match several empirical regularities. As in this paper, GHH preferences have been formulated by other authors, when evaluating macroeconomic policies, in order to prevent a counterfactual increase in labor supply during crises (see, e.g., Bianchi and Mendoza, 2018).

[16]The specification of the CES aggregator for liquidity services, z_t, resembles that of Drechsler et al. 2017: the weighting parameters with which the different forms of central bank money enter the CES aggregator (in this case, cash and CBDC) are normalized to unity and the weighting parameter of bank deposits, ω_d, is allowed to differ and can be calibrated in order to capture the difference in liquidity preferences between public and private money.

[17]f_m and f_{mm} denote the first and second derivate of $f(m_t)$ with respect to cash holdings, m_t, respectively.

[18]Alternatively, we could have accounted for the technological superiority of CBDC, relative to cash, by allowing for cash and CBDC to weigh differently in the CES aggregator and in the utility function (see, e.g., Ferrari Minesso et al. 2022). Feenstra 1986 shows that there is a broad range of specifications for which assuming a money-in-utility function is equivalent to having liquidity costs in the budget constraint. The motivation for our modelling choice

Note that this specification of the representative saver's problem allows for heterogeneous degrees of substitutability across different pairs of monetary instruments. For the shake of simplicity, the elasticity of monetary substitution, η_z, is assumed to be identical across all such pairs. However, the degree of substitutability across each pair of forms of money can be further calibrated and differentiated by setting the values of parameters ω_d and ψ_m.

3.1.2 Impatient Households: net borrowers

Let $c_{i,t}$, $n_{i,t}$, and $h_{i,t}$ represent consumption, hours worked and housing demand by impatient households in period t. Then, the representative impatient household maximizes

$$E_0 \sum_{t=0}^{\infty} \beta_i^t \left\{ \frac{1}{1-\sigma_h} \left[c_{i,t} - \frac{n_{i,t}^{1+\phi}}{(1+\phi)} \right]^{1-\sigma_h} + j_{i,t} \log h_{i,t} \right\}, \tag{7}$$

subject to a sequence of budget constraints and a borrowing limit

$$c_{i,t} + q_t \left(h_{i,t} - h_{i,t-1} \right) + R_{i,t-1} \frac{l_{i,t-1}}{\pi_t} + \left(1-\omega_T\right) T_t = l_{i,t} + w_t n_{i,t} \tag{8}$$

$$l_{i,t} \leq m_{H,t} E_t \left(\frac{q_{t+1}}{R_{i,t}} h_{i,t} \pi_{t+1} \right). \tag{9}$$

where $\beta_i \in (0,1)$ is the impatient households' subjective discount factor ($\beta_i < \beta_p$) and $j_{i,t} = j_i \varepsilon_{h,t}$ denotes a possibly time-varying preference parameter for housing, with $j_i > 0$. Bank loans obtained by impatient households are denoted by $l_{i,t}$ and the gross interest rate on loans to impatient households by $R_{i,t}$. According to (8), in each period, impatient households devote their available resources in terms of wage earnings and bank loans to consume, demand housing, repay their debt and pay lump-sum taxes. Expression (9) dictates that the borrowing capacity of impatient households is tied to the value of their collateral. In particular, they cannot borrow more than a possibly time-varying fraction $m_{H,t}$ of the expected value of their real estate stock. More precisely, $m_{H,t} = m_H \varepsilon_{mh,t}$ is the exogenously time-varying loan-to-value ratio, where $m_H \in [0,1]$ and $\varepsilon_{mh,t}$ captures exogenous shocks to constrained households' collateral.

3.1.3 Banks

Let $\Lambda_{t,t+1} = \beta_p \frac{\lambda_{t+1}^p}{\lambda_t^p}$ be the stochastic discount factor (with λ_t^p being the Lagrange multiplier of the patient households' optimization problem) and $\Omega_{b,t}$ earnings distributed by banks. Then, the

is twofold. First, acknowledging that there is still uncertainty about many of the design features that CBDCs will have in advanced economies, we assign the same weight (in the CES aggregator) to cash and CBDC on the basis that the Eurosystem has a preference for a digital euro to be as similar as euro-denominated banknotes as possible (ECB 2020). Second, the assumption of cash storage costs is based on a well documented evidence on which other models with CBDC also rely (see, e.g., Muñoz and Soons 2023).

representative bank manager maximizes

$$E_0 \sum_{t=0}^{\infty} \Lambda_{t,t+1} \quad f\left(\Omega_{b,t}\right) \tag{10}$$

subject to a balance sheet identity, a sequence of cash flow restrictions, a borrowing constraint, a liquidity (reserves) requirement and a central bank collateral requirement, respectively:

$$L_{i,t} + L_{e,t} + b_{b,t} + \widetilde{R}_{b,t} = e_t + D_t + f_t, \tag{11}$$

$$\Omega_{b,t} + e_t - (1-\delta^e)\frac{e_{t-1}}{\pi_t} = \frac{\left(r_{i,t-1}L_{i,t-1} + r_{e,t}L_{e,t-1} + r_{g,t-1}b_{b,,t-1} + r_{\widetilde{R},t-1}\widetilde{R}_{b,t-1} - r_{d,t-1}D_{t-1} - r_{f,t-1}f_{t-1}\right)}{\pi_t}, \tag{12}$$

$$D_t + f_t \leq \gamma_i L_{i,t} + \gamma_e L_{e,t} + \gamma_b b_{b,t} + \gamma_{\widetilde{R}}\widetilde{R}_{b,t}, \tag{13}$$

$$\theta_{R,t}D_t \leq \widetilde{R}_{b,t}, \tag{14}$$

$$f_t \leq \theta_{b,t}E_t\left(\frac{b_{b,t}}{R_{f,t}}\pi_{t+1}\right). \tag{15}$$

Bank assets comprise loans extended to impatient households, $L_{i,t}$, and entrepreneurial firms, $L_{e,t}$, government bonds, $b_{b,t}$, and reserves held at the central bank, $\widetilde{R}_{b,t}$.Formally, $A_{b,t} = L_{i,t} + L_{e,t} + b_{b,t} + \widetilde{R}_{b,t}$. Identity (11) states that total bank assets are financed by the sum of bank equity, e_t (also referred to as bank capital), deposits held by patient households, D_t, and central bank funding, f_t.[19]

The model assumes full inside equity financing, in the sense that bank equity is solely accumulated out of retained earnings. Formally, the law of motion for bank capital reads[20]

$$e_t = J_{b,t} - \ \Omega_{b,t} + \ (1-\delta^e)e_{t-1}/\pi_t, \tag{16}$$

[19]Without loss of generality and for empirically-relevant purposes, we assume that $f\left(\Omega_{b,t}\right) = (1 - 1/\sigma)^{-1}{\Omega_{b,t}}^{(1-1/\sigma)}$, where σ denotes the elasticity of intertemporal substitution in bank dividends. According to the evidence, dividend smoothing operates through two main channels; owners (i.e., patient households)' risk aversion and managers' propensity to smooth dividends (see, e.g., Wu 2018). See Iacoviello (2015) for a DSGE model with financial institutions maximizing an objective function that is also concave in dividends and Muñoz 2021 for a model that replicates certain moments of euro area bank dividends by assuming that both, owners and managers are risk averse.

[20]Expression (16) for the law of motion for bank capital is identical to the one assumed in Muñoz (2021) and only differs from the one proposed in Gerali et al. (2010) in that these authors assume net profits are fully retained, period by period (i.e., there is no bank payout policy whatsoever).

where $J_{b,t}$ stands for bank net profits. Rearranging in expression (16), bank net profits can be decomposed into three terms:

$$J_{b,t} = \underbrace{\underbrace{(e_t - e_{t-1}/\pi_t)}_{\text{reinvested profits}} + \underbrace{(\delta^e e_{t-1}/\pi_t)}_{\text{eroded equity}}}_{\text{retained earnings}} + \underbrace{\Omega_{b,t},}_{\text{distributed earnings}} \tag{17}$$

where the term $(e_t - e_{t-1}/\pi_t)$ refers to the part of profits made in period t which are reinvested in the financial intermediation business, and $(\delta^e e_{t-1}/\pi_t)$ is the fraction of bank own resources which, due to exogenous factors, cannot be further accumulated as bank capital into the next period. The term $(\delta^e e_{t-1}/\pi_t)$ can be interpreted in several manners: (i) own resources the banker devotes to manage bank capital and to play its role as financial intermediary, or (ii) equity that erodes due to a variety of factors which are not explicitly accounted for in the model and which may relate to specific characteristics of bank capital such as its quality.

Equation (12) is a flow of funds constraint which states that, in each period, the bank manager has to distribute net profits, $J_{b,t}$, between dividend payouts, $\Omega_{b,t}$, and retained earnings. In the model, bank net profits are defined as the net interest income (i.e., right hand side of equation 12). Note that $r_{i,t}$, $r_{e,t}$ $r_{g,t}$, $r_{\widetilde{R},t}$, $r_{d,t}$ and $r_{f,t}$ denote the net interest rates on loans to impatient households, loans to entrepreneurial firms, government bonds, reserves, deposits and central bank funding, respectively.

Expression (13) stipulates that banks are constrained in their ability to issue liabilities (i.e., deposits and central bank funding). For a given period t, deposits and central bank financing cannot exceed total risk-weighted assets. γ_i, γ_e, γ_b and $\gamma_{\widetilde{R}}$ denote the proportions of loans to households, loans to firms, government bonds and reserves that can be financed with debt. Given that this expression is binding in a neighborhood of the steady state, $(1-\gamma_h)$ can be interpreted as the sectoral capital requirement on holdings of asset class h (for $h = e,\ i,\ b,\ \widetilde{R}$) and expression (13) as a capital adequacy constraint.

Expression (14) dictates that reserves held by the representative bank in the central bank cannot fall below a certain threshold specified as a possibly time-varying fraction,$\theta_{R,t}$, of deposits, where $\theta_R \in (0,1)$ and $\varepsilon_{\theta_r,t}$ captures exogenous shocks to banks' relative reserve holdings. This expression can be interpreted as a liquidity (reserves) requirement faced by banks and it is relevant due to various quantitative and empirically - related reasons. First, an important fraction of total central bank liabilities is represented by reserves and, thus, modelling them allows to improve the model fit (see section 3.3). Second, outside periods of unconventional monetary policy and/or extraordinary uncertainty, the reserve-to-deposits ratio of the euro area banking sector has been very stable over time. Third, expression (14) permits to capture the idea that, in practice, banks are expected to adjust in response to any CBDC-induced deposit withdrawal by drawing down reserves up to the point in which their internal target for the reserves ratio is met.[21]

According to expression (15), the capacity of banks to obtain funding from the monetary authority is tied to the value of its collateral, which in the baseline model is assumed to be government bonds.[22] In particular, banks cannot borrow from the central bank more than a possibly time-varying fraction, $\theta_{b,t}$, of the expected value of their government bond holdings, where $\theta_{b,t} = \theta_b \varepsilon_{\theta_b,t}$ can be interpreted as the complement of the exogenously time-varying haircut on government bonds, $\theta_b \in [0,1]$ and $\varepsilon_{\theta_b,t}$ captures exogenous shocks to banks' collateral (for central bank operations).

3.1.4 Non-financial Corporations

Non-financial corporations in this model economy include entrepreneurial firms, capital goods producers and final goods producers.The entrepreneurial firm industry is populated by two types of agents. For each entrepreneurial firm, there is a manager who obtains bank lending to acquire new housing in the form of commercial real estate and a retailer who rents such input and combines it with physical capital and labor (through a Cobb-Douglas technology) to produce intermediate goods under monopolistic competition. Here, we briefly present the problem of the entrepreneurial manager. For all the details on the problems of entrepreneurial retailers, capital goods producers and final goods producers, we refer the reader to Appendix C.

Let $\Omega_{e,t}$ be earnings distributed by entrepreneurs. Then, entrepreneurial managers seek to maximize

$$E_0 \sum_{t=0}^{\infty} \Lambda_{t,t+1} \quad f\left(\Omega_{e,t}\right)$$

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

$$\Omega_{e,t} + R_{e,t} \frac{l_{e,t-1}}{\pi_t} + q_{k,t} \left[k_{e,t} - (1-\delta_t^k) k_{e,t-1}\right] + q_t (h_{e,t} - h_{e,t-1}) = r_{k,t} u_t k_{e,t-1} + r_{h,t} h_{e,t-1} + l_{e,t} + J_{er,t}, \quad (18)$$

$$l_{e,t} \leq m_{K,t} E_t \left[\frac{q_{k,t+1}}{R_{e,t+1}} (1-\delta_{t+1}^k) k_{e,t} \pi_{t+1}\right], \quad (19)$$

where $l_{e,t}$ denotes bank loans extended to entrepreneurial firms, $k_{e,t}$ refers to physical capital, u_t is its utilization rate and $J_{er,t}$ are distributed profits obtained from the ownership of intermediate

[21] Individual banks' internal targets for their reserves ratio are usually specified by adding a buffer to the reserves that are strictly neccesary to comply with regulations on liquidity requirements and minimum reserves. For a CBDC analysis based on a set up that offers a careful modelling of the interbank market, and allows for heterogeneous bank reserve holdings and excess reserves in equilibrium, see Abad et al. (2023).

[22] See section 3.3 for a version of the collateral requirement under which multiple asset types are eligible as collateral.

good producing firms (i.e., entrepreneurial retailers). $R_{e,t}$ denotes the gross interest rate on bank loans to firms and $q_{k,t}$ is the price of physical capital. $r_{k,t}$ and $r_{h,t}$ denote the net interest rates that entrepreneurial managers charge when renting physical capital and commercial real estate to entrepreneurial retailers, respectively. The depreciation rate of capital is an increasing and convex function of the rate of capacity utilization

$$\delta_t^k(u_t) = \delta_0^k + \delta_1^k(u_t - 1) + \frac{\delta_2^k}{2}(u_t - 1)^2. \tag{20}$$

According to (18), in each period, entrepreneurial managers devote their available resources in terms of loans and rents to distribute earnings, repay their debt, and accumulate physical capital, $k_{e,t}$, and commercial real estate, $h_{e,t}$. Expression (19) dictates that the borrowing capacity of entrepreneurial firms is tied to the value of their physical capital collateral. In particular, they cannot borrow more than a possibly time-varying fraction $m_{K,t} = m_K \varepsilon_{mk,t}$ of the expected value of their capital stock, where $m_K \in [0, 1]$ and $\varepsilon_{mk,t}$ captures exogenous shocks to entrepreneurial firms' collateral.[23]

3.1.5 Government

The government collects tax revenues from households in a lump-sum fashion. Such revenues are determined according to a fiscal rule

$$T_t = \phi_p b_{p,t-1} + \phi_b b_{b,t-1}, \tag{21}$$

where $\phi_p > 0$ and $\phi_b > 0$ determine the response of tax revenues to changes in government bond holdings of patient households and banks, respectively.

Government spending is assumed to be equal to a constant fraction, $\varrho > 0$, of steady state output

$$G_t = \varrho Y^{ss}. \tag{22}$$

Consequently, the issuance of short-term government bonds, $B_{g,t}$, is endogenously determined by the intertemporal budget constraint of the government

$$G_t + r_{g,t-1}\frac{B_{g,t-1}}{\pi_t} = T_t + \Omega_{cb,t} + \left(B_{g,t} - \frac{B_{g,t-1}}{\pi_t}\right). \tag{23}$$

According to expression (23), in each period, the government devotes its available resources in

[23] As for the case of bank managers and for empirically-relevant purposes, we assume that $f(\Omega_{e,t}) = (1 - 1/\sigma)^{-1}{\Omega_{e,t}}^{(1-1/\sigma)}$.

terms of tax revenues, T_t, central bank profits, $\Omega_{cb,t}$, and funds obtained from the issuance of bonds, $\left(B_{g,t} - \frac{B_{g,t-1}}{\pi_t}\right)$, to consume, G_t, and to repay its debt, $r_{g,t-1}\frac{B_{g,t-1}}{\pi_t}$.

3.1.6 Central Bank

The central bank sets two nominal short-term policy rates: the lending policy rate (also referred to as the lending facility rate), $r_{f,t}$, and the interest rate on reserves (also referred to as the deposit facility rate), $r_{\widetilde{R},t}$. The former is the interest rate the central bank charges when providing the banking sector with funding and is set according to a Taylor-type policy rule:

$$r_{f,t} = \rho_r r_{f,t-1} + (1-\rho_r)\left(r_f^{ss} + \alpha_\pi \tilde{\pi}_t + \alpha_Y \tilde{y}_t\right) + e_{rf,t}, \tag{24}$$

where ρ_r is the interest rate smoothing parameter, r_f^{ss} is the steady-state lending policy rate, $\alpha_\pi > 1$ determines the response of the lending policy 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 same policy rate to output growth, $\tilde{y}_t = \log(Y_t/Y_{t-1})$, and $e_{rf,t}$ is a white noise shock to the lending facility rate.

The deposit facility rate is the interest rate at which bank reserves are remunerated. This policy rate is assumed to be set such that a constant corridor of width $\mu > 0$ is maintained between the lending facility rate and the deposit facility rate,

$$r_{\widetilde{R},t} = r_{f,t} - \mu. \tag{25}$$

Central bank assets consist of lending to banks and are financed by the sum of reserves, cash and central bank digital currency. Formally:

$$F_t = \widetilde{R}_t + M_t + CBDC_t. \tag{26}$$

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

$$\Omega_{cb,t} = \widetilde{R}_t + M_t + CBDC_t + R_{f,t-1}\frac{F_{t-1}}{\pi_t} - R_{\widetilde{R},t-1}\frac{\widetilde{R}_{t-1}}{\pi_t} - \frac{M_{t-1}}{\pi_t} - R_{cbdc,t-1}\frac{CBDC_{t-1}}{\pi_t} - F_t. \tag{27}$$

Finally, the central bank issues central bank digital currency according to a policy rule, which - for the most general case - stipulates that CBDC supply in period t is equal to a constant fraction,

$\phi_Y \geq 0$, of steady state real output.[24] Formally

$$CBDC_t = \phi_Y Y^{ss}. \tag{28}$$

As discussed in section 4, under the baseline (counterfactual) scenario, the central bank does not issue CBDC (i.e., $\phi_Y = 0$). The quantitative analysis presented in that section considers various alternative CBDC policy scenarios which differ from one another in the specification and/or calibration of the CBDC policy rule in order to carry out a counterfactual analysis and assess the main implications for bank intermediation, the real economy and welfare of various CBDC quantity and interest rate type of policy rules.

3.1.7 Aggregation and Market Clearing

In equilibrium, all markets clear. 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 private consumption, C_t, final public consumption, G_t, investment, $q_{k,t}I_t$, and resources to do both; manage the capital position of the bank, $\delta^e e_{t-1}$ (also interpretable as eroded equity), and hold cash, $f(m_t)$:

$$Y_t = C_t + q_{k,t}I_t + G_t + \delta^e e_{t-1} + f(m_t).$$

The supply in all markets is endogenous with the exception of housing supply, which is specified as a fixed endowment that is normalized to unity

$$\overline{H} = h_{p,t} + h_{i,t} + h_{e,t}.$$

3.2 Calibration

We follow a three-stage strategy in order to calibrate the model to quarterly euro area data for the period 2000:I-2021:II.[25] First, several parameters are set following convention (Table 3). The inverse of the Frisch elasticity of labor is set to a value of 1, whereas the risk aversion parameter of household preferences is fixed to a standard value of 2. Parameter ω_T is set to a value of 0.5 so that

[24]The choice of this specification for the CBDC policy rule under the most general case is motivated by the wide academic and policy discussion on the desirability of counting with a constant limit on individual CBDC holdings as a tool to calibrate the quantity of central bank digital currency in circulation. See, e.g., Bindseil, U., and F. Panetta (2020), "CBDC remuneration in a world with low or negative nominal interest rates." VoxEU column, 5 October 2020, and Panetta, F., (2021). Interview with Der Spiegel, 9 February 2021 (see Table A.1).

[25]All time series expressed in Euros are seasonally adjusted and deflated. With regards to the matching of second moments, the log value of deflated time series has been linearly detrended before computing standard deviation targets. All details on the dataset constructed for calibration purposes are available in Appendix B.

each group of households accounts for 50% of collected taxes. Regarding the dynamic depreciation rate of physical capital δ_t^k; δ_0^k is fixed to a standard value of 0.025 while, following convention, δ_1^k and δ_2^k are defined as specific fractions of the steady state interest rate on physical capital. Based on the evidence for the euro area and on the literature, the loan-to-value on residential mortgages, m_H, is set to a value of 0.7 (see, e.g., Gerali et al. 2010; Muñoz 2021). Since the risk weights of reserves and government bonds are both equal to 0 under the Basel III accord, the fraction of bank reserves and government bonds that can be financed with bank debt is assumed to be equal to one (i.e., $\gamma_{\widetilde{R}} = 1$, $\gamma_b = 1$). The elasticity of substitution between intermediate goods is fixed to a value of 6. The Calvo parameter, the inflation indexation parameter and the three parameters of the Taylor rule (i.e., ρ_r, α_Y, and α_π) are fixed to values of 0.82, 0.23, 0.9, 0.1 and 2.5, within the range of values typically obtained when calibrating or estimating a DSGE model to quarterly data of the euro area (see, e.g., Smets and Wouters 2003; Gerali et al. 2010; Coenen et al. 2018). The autoregressive coefficients in the AR(1) processes followed by all shocks are set equal to 0.90.

Second, another group of parameters is calibrated by using steady state targets (Tables 4, 5, and 6). Some of these targets are intended to ensure that the weight of all key financial assets and monetary instruments in the balance sheets of the Eurosystem and the euro area banking sector is taken into account .[26] The size of the central bank balance sheet is proxied by the sum of cash (i.e., banknotes in circulation) and reserves (i.e., liabilities to euro area credit institutions related to monetary policy operations denominated in euro), which are the two central bank liabilities available under the baseline scenario.[27] Similarly, the size of the euro area banking sector's consolidated balance sheet is proxied by the sum of total bank loans to households and firms, government debt held by credit institutions and bank reserves.

The patient households' discount factor, $\beta_p = 0.993$, is chosen such that the annual interest rate on bank deposits equals 2.3%. The impatient households' discount factor is set to 0.980, in order to generate an annualized lending-deposit spread of 3.05%. Household weights on housing utility, j_p and j_i, have been calibrated to match the private consumption-to-GDP ratio and the household loans-to-GDP ratio, respectively. The weight of liquidity services in the utility function of patient households is set to 0.0541, which is consistent with a cash-to-GDP ratio of around 0.33. The weight parameter of deposits, the elasticity of substitution across monetary instruments, and the cash storage cost parameter have been calibrated to match the bank deposits-to-assets ratio, the annualized reserves-deposit spread, and the cash-to-central bank assets ratio, respectively. As already explained in section 3.1, these three parameters govern the degree of substitutability across

[26] Of course, many of these model-based steady state ratio targets are larger than what they are in reality, as there are various assets held by banks and the central bank in practice whose modelling has been omitted. However, since the relative weight of each asset is respected and the bulk of key assets playing a role in the transmission process is modelled, this simplification should not affect the main findings of the quantitative analysis.

[27] From a quantitative perspective, the sum of these two central bank liabilities have represented the bulk of total central bank liabilities over the entire sample (i.e., 2000:I-2021:II).

each of the three pairs of monetary instruments.[28] Importantly, since the Eurosystem has not made a decision yet on various CBDC design features that are likely to affect the value of at least some of these parameters, section 4.3 evaluates the robustness of the main findings of our analysis to changes in these parameters. The loan-to-value ratio on loans to entrepreneurial firms, m_K, is set to 0.214, which is consistent with a weight of loans to firms in total bank assets of 0.37. The shares in production of physical capital, α, and commercial real estate, ν, are set to match an investment-to-GDP ratio of 0.21 and a corporate loans-to-GDP ratio of 1.68.

With regards to bank parameters, we proceed as follows. The fractions of residential mortgages and corporate loans that can be financed with bank debt are fixed to 0.92 and 0.895, which are consistent with a household lending-to-bank assets ratio of 0.43 and a bank equity-to-loans ratio of roughly 0.105.[29] The depreciation rate of bank capital, δ^e, is set to 0.071 in order to allow for a bank reserves-to-assets ratio of 0.072. Reserves and central bank collateral requirements, θ_R and θ_b, are set to 0.0874 and 0.995 to match a reserves-to-GDP ratio of 0.33 and a central bank funding-to-assets ratio of 0.089, respectively.

As far as policy parameters are concerned, the response parameters of the fiscal rule, ϕ_{Bp} and ϕ_{Bb}, are chosen to generate a bank government bonds-to-GDP ratio of 0.61 and a bank government bonds-to-assets ratio of 0.13, respectively. The parameter of the government spending equation, ϱ, is fixed to 0.207 in line with the data target for the steady state public consumption-to-GDP ratio. 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 parameter that determines the constant corridor between the lending policy rate and the deposit facility rate, μ, is set to match an annualized spread between the two policy rates of 1.39%. Finally the parameter of the CBD quantity rule, $\phi_{Y^{ss}}$, is fixed to 0 to ensure that, under the baseline scenario, there is no CBDC in circulation and to allow for a reserves-to-central bank assets ratio of 0.499.

Third, the size of shocks and other parameters affecting the dispersion of key aggregates are calibrated to improve the fit of the model to the data in terms of relative volatilities (see Tables 7 and 8). The investment adjustment cost parameter ψ_I is set to target a relative standard deviation of investment of 3.1 % while the relative volatility of bank dividends is matched by calibrating the elasticity of intertemporal substitution (EIS) in bank dividends. The size of the nine different types of shocks that hit this model economy have been calibrated to match the second moment

[28] Recall that the weight parameters of cash and CBDC in the liquidity services aggregator are normalized to unity. The weight parameter of deposits permits to account for the difference in liquidity preferences between public and private money and, overall, the calibration of these three parameters (i.e., ω_d, η_z, and ψ_m) allows for capturing the differences in the degree of substitutability between two forms of money across all pairs of monetary instruments.

[29] These values and the fact that, in the baseline calibration model, sectoral capital requirements on corporate loans are relatively higher than those imposed on residential mortgages is consistent with existing (Basel III) capital regulation.

(in terms of relative standard deviations) of GDP, total consumption, cash, reserves, central bank assets, bank loans, bank equity, bank deposits and the interest rate on bank deposits.

3.3 Transmission mechanism and steady-state effects of issuing CBDC

In this section we investigate the transmission mechanisms and steady state effects on the banking sector and the economy of issuing a fixed supply of CBDC as in policy rule (28). We consider four cases that differ in the amount of CBDC issued: $\Psi = (\phi_{Y,0};\ \phi_{Y,1};\ \phi_{Y,2};\ \phi_{Y,3}) = (0.00;\ 0.25;\ 0.45;\ 0.644)$. The baseline case, $\phi_Y = 0.0$, is the calibrated model with zero supply of CBDC. The fourth case, $\phi_Y = 0.644$, is the case where the central bank sets the interest rate on CBDC equal to zero like with cash and provides an elastic supply of CBDC at that rate. With our calibration this results in a steady-state supply of CBDC of 64 percent of quarterly GDP. In addition we consider two intermediate cases with a supply of CBDC of 25 and 45 percent of GDP respectively. Note that the steady-state equilibrium interest rate on CBDC is negative in those cases because holding cash which earns a zero interest rate carries holding costs.

Figure 4 plots the steady state level of selected aggregates under these four scenarios. The transmission of CBDC can be summarized into four main mechanisms: (i) imperfect substitutability across monetary intruments and an aggregate increase of liquidity services, (ii) an expanded and more profitable central bank balance sheet, (iii) partial bank disintermediation as banks substitute relatively cheap deposit funding for more costly central bank borrowing, and (iv) a fiscal expansion due to the rise in seigniorage. Each row of Figure 4 captures the main elements of each of these four broad transmission mechanisms. Figure 5 illustrates how the balance sheets of the central bank and the banking sector - as well as key interest rates - structurally adjust in response to the issuance of a CBDC under the scenario for which $\phi_Y = 0.644$ (i.e., $r_{cbdc}^{ss} = 0$).

The next subsections expand on these four mechanisms and show how they depend on some of the key structural parameters. Overall, we find that due to the imperfect substitutability across monetary instruments, the introduction of a CBDC leads to a liquidity services expansion (i.e., the increase in CBDC more than compensates the joint reduction in cash and deposit holdings). As a result, the central bank balance sheet expands and its profitability increases. The latter follows from the fact that in equilibrium CBDC carries a smaller, negative, interest rate than cash and reserves. The banking sector compensates the loss in deposit funding with an increased reliance on central bank lending. This increases the overall cost of funding as the interest rate on central bank lending is higher than the one on deposits. On the asset side of the banking sector, bank holdings of eligible collateral (i.e., government bonds) increase at the expense of loans to the private sector (which are more profitable). Overall, bank net interest margins unambiguously compress, resulting in lower bank equity, further reducing lending to the private sector and amplifying the CBDC induced bank disintermediation effect. Everything else equal, this negative credit supply effect leads to a fall in steady state output. However, CBDC also triggers a fiscal expansion that helps mitigating the adverse real effects of disintermediation. Increased seigniorage due to the expansion of the central bank balance sheet and an increased demand for bonds by banks relaxes the intertemporal government budget constraint and leads to a fall in steady state taxes which fosters consumption and output. In the baseline calibration, we find that the net effect is a small drop in steady-state output.

3.3.1 Imperfect Substitutability and Liquidity Services Expansion

The imperfect substitutability across the three monetary instruments has key implications of CBDC issuance for liquidity services. As shown in the first line of figure 4 CBDC only partially replaces cash and bank deposits. CBDC substitutes for these two forms of money up to the point in which the marginal utility of holding each of the three monetary instruments for patient households is equal. Aggregate liquidity services soar since the increase in demand for CBDC more than compensates the joint decline in cash and deposit holdings.[30]

From the demand side, the magnitude of these substitution effects and the equilibrium level of interest rates on CBDC and bank deposits crucially depend on the elasticity of substitution across monetary instruments ($\eta_z > 1$), cash storage costs ($\psi_m > 0$) and the relative liquidity preference for public money ($\omega_d < 1$). As shown in Figure 6, the increase in liquidity services is decreasing in the elasticity of substitution across monetary instruments. Similarly, it increases with cash storage costs and with the relative liquidity preference for private money (see Figure D.1 and Figure D.2 in Appendix D). The size of the negative CBDC-induced steady state impact on real GDP increases with the demand for liquidity services, z_t, and negatively depends on the degree of substitutability across forms of money (Figure 6).

3.3.2 Central Bank Balance Sheet (and Profits) Expansion

As shown in the second line of Figure 4 and Figure 5, the expansion of liquidity services induced by the issuance of CBDC leads to an expansion of the central bank's balance sheet and profitability. The magnitude of this expansion depends on the minimum reserve requirement. Expression (14) stipulates that, for every unit of deposits that are withdrawn, bank reserves decrease by θ_R units.[31] That is, steady state reserves decrease - less than proportionally to deposits - with the amount of CBDC in circulation (Figure 4). This translates into an expansion of the central bank balance sheet since the increase in CBDC is never fully compensated by the joint decline in the rest of

[30] For a given level of income, this portfolio re-balancing effect towards more money holdings implies that savers adjust their demand for other asstes and/or goods downwards (e.g., government bonds).

[31] Recall that, in this model economy, reserve requirements are binding in a neighbourhood of the steady state.

central bank liabilities (i.e., cash and reserves).[32]

This CBDC-induced expansion of the central bank balance sheet has a positive impact on central bank profits from both the asset and the liability side. First, assets held by the central bank increase while the interest rate on such assets is only marginally affected (Figure 5). Second, there is a change in the composition of central bank liabilities entailing a partial shift from costly liabilities (i.e., reserves) to profitable or costless liabilities (i.e., CBDC).[33] Overall, seigniorage transferred by the central bank to the government will increase.

As shown in Figure 7, the higher the bank reserves ratio is (i.e., the higher the value of θ_R), the larger the fraction of the CBDC issuance that is absorbed by drawing down reserves and, consequently, the lower the expansion of the central bank balance sheet and the smaller the negative steady-state effect on GDP. [34]. As shown in Abad et al. (2023), if excess reserves are sufficiently large, and reserves and deposits are remunerated at the same rate (in a floor system), and there is no central bank collateral requirement, reserves will fall one-for-one with deposits and the central bank balance sheet expansion induced by the imperfect substitutability across monetary instruments will have no impact on bank intermediation and the macroeconomy.

3.3.3 Bank Disintermediation

As shown in the third line of Figure 4 and in Figure 5, the reduced demand for deposits leads to a rise in central bank borrowing, an increase in the demand for government bonds which are needed as collateral, and a drop in lending to the private sector. The compression of the lending margin triggered by the rebalancing effects on the balance sheet of banks leads to lower capital and a deleveraging which negatively impacts steady-state GDP. Next, we elaborate a bit more on those partial bank disintermediation effects.

Bank lending margin compression As shown in Figure 5, the weighted average return on loans to households and firms is larger than the return on government bond holdings and the cost of central bank funding is higher than that of household deposits. Therefore, the increase in the share of central bank funding at the expense of deposits and that in the share of government debt at the expense of lending to the private sector lead to a compression in the bank net interest margin from both the asset and the liability side. In addition, note that in response to the fall in

[32]Note that this is always going to be the case precisely due to the imperfect substitutability between CBDC and the other two forms of money and the range of values that the reserves requirement parameter, $\theta_R \in (0,1)$, can take. In particular, and since the fall in reserves is more moderate than that in deposits, it follows that the steady state expansion of the central bank balance sheet is larger than the one of liquidity services.

[33]Recall that, under the baseline calibration and for the considered CBDC scenarios, $r^{ss}_{\widetilde{R}} > 0$ whereas $r^{ss}_{cbdc} \leq 0$.

[34]For a more comprehensive and institutional analysis of the different channels through which the banking sector and the central bank balance sheets can adjust in response to the introduction of a CBDC, see Adalid et al. (2022)

the demand for deposits, the interest rate on deposits rises more than the interest rate on loans, leading to a reduction in the interest rate margin.

Capital requirements Given the assumption of full inside equity financing (expression 16), the fact that bank profits decrease with the amount of CBDC in circulation implies that bank equity follows a similar pattern (see Figure 4). How does this effect transmit to bank assets through capital requirements? Combining expressions (11) and (13), recalling that the latter is binding in a neighbourhood of the steady state, and taking into account that the risk weights of reserves and government bonds are equal to zero (i.e., $\gamma_{\widetilde{R}} = 1$, $\gamma_b = 1$), bank equity can also be expressed as:

$$e_t = (1 - \gamma_i) L_{i,t} + (1 - \gamma_e) L_{e,t}. \tag{29}$$

That is, the downward adjustment in bank assets that is required to meet capital requirements in response to the CBDC-induced reduction in bank capital is fully borne by lending. The introduction of CBDC in the presence of capital requirements triggers a deleveraging effect.

Somewhat paradoxically, the magnitude of this deleveraging effect decreases with the level of capital requirements (see Figure D.3). Intuitively, the proportion of bank assets that is financed with deposits (i.e., banks' reliance on deposit funding) decreases with capital requirements. Therefore, the magnitude of the CBDC-induced re-balancing effects and the related compression in bank interest margins decrease with regulatory capital ratios.

Collateral requirements An important parameter determining the rebalancing of the bank's balance sheet is the collateral requirement for central bank borrowing (θ_b). In the baseline model, the only type of asset that is eligible as collateral in monetary policy operations is assumed to be government bonds. In this case, the introduction of a CBDC unambiguously leads to an increase not only in the share of central bank funding in total bank liabilities but also in the share of government debt in total bank assets. As a consequence, the share of all other bank assets, including lending, declines (Figure 5). Figure 8 shows the impact of higher haircuts on government bonds. Higher haircuts lead to a larger expansion of the central bank balance sheet, but also a larger fall in bank profitability, bank equity and output as the implicit cost of central bank funding needed to make up for the loss in deposits goes up.

In practice, the collateral framework often allows for different eligible asset classes, usually differing from one another in their associated haircut and in their weight in the collateral pool. Consider the following general version of equation (15):

$$f_t \leq \sum_{i=1}^{N} \theta_{i,t} E_t \left(\frac{Q_{i,t}}{R_{f,t}} \pi_{t+1} \right), \tag{30}$$

where $Q_{i,t}$ denotes holdings of eligible asset "i" by the representative bank in period t, N is the number of eligible assets, and $\theta_{i,t}$ refers to the possibly time-varying fraction of asset "i" holdings that can be financed with central bank funding. Interestingly, under specification (30) of collateral requirements, $\theta_{i,t}$ can be interpreted not only as the complementary of the haircut on asset "i" holdings, but also as the weight of such asset in the collateral pool.

Depending on which assets are eligible as collateral in monetary policy operations with the central bank and on how they weigh in the collateral pool, the steady state rebalancing effects on banks' balance sheets may vary and the impact of CBDC on bank lending may differ. In general, any negative impact that a CBDC-induced central bank balance sheet expansion may have on the steady state level of a particular bank asset class diminishes with the weight of such asset type in the collateral pool. In the case of the Eurosystem collateral framework, not only government bonds but also loans to NFCs are eligible as collateral. Consider the following particular case within the general class of collateral requirements referred by expression (30):

$$f_t \leq \theta_{b,t} E_t \left(\frac{b_{b,t}}{R_{f,t}} \pi_{t+1} \right) + \theta_{l,t} E_t \left(\frac{L_{e,t}}{R_{f,t}} \pi_{t+1} \right), \tag{31}$$

where $\theta_{l,t} = \theta_l \varepsilon_{\theta l,t}$ provides information on the haircut on loans to firms as well as on the weight of this asset class in the collateral pool. Figure D.4 makes clear that as θ_l (and, thus, the weight of $L_{e,t}$ in the collateral pool) increases, the structural impact of issuing CBDC on bank lending to non-financial corporations and output diminishes.

3.3.4 Fiscal Expansion

As shown in the fourth line of Figure 4, the issuance of CBDC leads to a fall in taxes and an associated rise in private consumption. The relaxation of the intertemporal government budget constraint occurs through two channels. First and foremost, the increased size and profitability of the central bank balance sheet increases the seigniorage revenues that are transferred to the government. Second, the increased demand for collateral for central bank funding increases the demand for government bonds as discussed above. As a result and in line with the fiscal reaction function, taxes will fall. The fall in taxes raises private consumption and output.

Overall, a careful inspection of the transmission channels through which steady state CBDC effects operate, permits to conclude that, despite the fiscal expansion, the bank disintermediation effect dominates and the net structural impact of CBDC on bank profitability, lending and real GDP is negative.[35] These findings resemble three important conclusions that can be drawn from the

[35] As the transmission mechanisms of a temporary CBDC issuance are analogous to those that apply to steady state effects of CBDC, we refer the reader to Appendix D for a graphic representation of the impulse responses of selected aggregates to a persistent CBDC supply shock (Figure D.5). There, we slightly modify equation (28) as $CBDC_t = \phi_{Y,t} Y^{ss}$, where CBDC in period t is now assumed to be a possibly time-varying fraction, $\phi_{Y,t} = \phi_Y \varepsilon_{cbdc,t}$,

empirical evidence presented in section 2. First, the magnitude of the CBDC structural impact (or net steady state effect) on bank valuations and lending crucially depends on the amount of CBDC in circulation. Second, the dominance of the bank disintermediation effect underscores the importance of the deposit ratio as a key factor to understand the transmission of CBDC-induced net steady state effects on the banking sector. Third, at the aggregate level, the net steady state impact of CBDC on bank valuations, lending to NFCs and real GDP is moderate.

4 Welfare Analysis

This section evaluates the welfare effects and trade-offs of issuing CBDC and derives optimal simple CBDC policy rules. This permits us to obtain a range of values for the optimal amount of CBDC in circulation and to study the main steady state and cyclical consequences of supplying CBDC under optimal CBDC policy rules.

4.1 CBDC Policy Regimes

First, we construct various CBDC policy scenarios that are compared with the baseline scenario of no CBDC supply (i.e., expression 28 with $\phi_Y = 0.00$). We consider both, CBDC quantity rules and interest rate rules and differentiate between dynamic and static rules.

4.1.1 CBDC quantity rules

Quantity rule (i) CBDC in period t is specified as a constant fraction, $\phi_Y > 0$, of quarterly real GDP:

$$CBDC_t = \phi_Y Y_t. \tag{32}$$

Quantity rule (ii) Under this scenario, CBDC in period t is specified as a constant fraction, $\phi_Y > 0$, of steady state quarterly real GDP:

$$CBDC_t = \phi_Y Y^{ss}. \tag{33}$$

While, under quantity rule (i), CBDC supply is time-varying and comoves with real GDP, under quantity rule (ii) CBDC issuance is constant over time. As mentioned in section 3.1, the latter case is particularly relevant from a policy perspective, since this policy option would be similar

of steady state real GDP, with $\phi_Y \geq 0$ and $\varepsilon_{cbdc,t}$ capturing exogenous CBDC supply shocks. The size of these shocks, σ_{cbdc}, is set equal to 0.1 and the autoregressive coefficient in the AR(1) process followed by these shocks, ρ_{cbdc}, is set equal to 0.90. It is worth noting, that in this case, the net impact of CBDC on real economic activity is positive as the fiscal expansion effect dominates the bank disintermediation effect.

to adopting a constant limit on individual CBDC holdings, a proposal that has been discussed by policymakers in the recent past.

Quantity rule (iii) In this case, the central bank sets CBDC supply according to the rule:

$$CBDC_t = \rho_{cbdc} CBDC_{t-1} + (1 - \rho_{cbdc}) \left[\phi_Y Y^{ss} + \phi_X \widetilde{X}_t \right], \tag{34}$$

where ρ_{cbdc} is the CBDC supply smoothing parameter, $\phi_Y Y^{ss}$ is the steady-state CBDC quantity (expressed as a proportion of steady state real output), and ϕ_X determines the response of CBDC supply to deviations of a macroeconomic indicator of the choice of the regulator, X_t, from its steady state level, $\bar{X}$; with $\widetilde{X}_t = \log(X_t/\bar{X})$. In what follows, we will typically choose real GDP as the variable the policy maker reacts to.

4.1.2 CBDC interest rate rules

Interest rate rule (i) Under this scenario, the interest rate at which CBDC holdings are remunerated is constant and equal to zero. Formally:

$$r_{cbdc,t} = 0. \tag{35}$$

The choice of this scenario is motivated by the fact that the existing version of central bank money (i.e., cash) is not remunerated. In what follows, we will also refer to this case as the unconstrained CBDC supply scenario and it will also be taken as a reference when assessing certain effects of optimal CBDC policy rules. See also section 3.3.

Interest rate rule (ii) The central bank sets the interest rate on CBDC holdings in period t as a constant fraction, $\phi_r > 0$, of the steady state interest rate on reserves, for $t = 0, 1, 2, ..$:

$$r_{cbdc,t} = \phi_r r_{\widetilde{R}}^{ss}. \tag{36}$$

Interest rate rule (iii) The monetary authority sets the CBDC interest rate according to the following rule:

$$r_{cbdc,t} = \phi_r r_{\widetilde{R},t}, \tag{37}$$

where $\phi_r > 0$ determines the response of the CBDC interest rate to changes in the deposit facility rate.[36]

[36] See Bindseil, U., and F. Panetta (2020), "CBDC remuneration in a world with low or negative nominal interest rates." VoxEU column, 5 October 2020 for a policy proposal according to which CBDC remuneration is pegged to the deposit facility rate (see Table A.1).

While the rate at which CBDC holdings are remunerated under interest rate rules (i) and (ii) is constant over time, under interest rate rule (iii) such rate comoves with the interest rate on reserves. Since the central bank sets $r_{\widetilde{R},t}$ so to maintain a constant corridor between the lending policy rate and the deposit facility rate (i.e., expression 25), it follows that - under interest rate rule (iii) - the interest rate on CBDC holdings comoves with the lending facility rate and, thus, is indirectly set according to a Taylor-type policy rule (i.e., expression 24).

4.2 Welfare Effects and Optimal CBDC Policy Rules

Then, we adopt a normative approach to investigate the welfare consequences of issuing central bank digital currency and the main implications of doing so under welfare-maximizing CBDC policy rules. In order to do so, a measure of social welfare - specified as a weighted average of the expected life-time utility of savers and borrowers - is maximized with respect to the corresponding policy parameter/s. Formally:

$$\arg\max_{\Theta} V_0 = \zeta_p V_0^p + \zeta_i V_0^i, \tag{38}$$

where $V_0^p = E_0 \sum\limits_{t=0}^{\infty} \beta_p^t u\left(c_{p,t}, h_{p,t}, n_{p,t}, z_t\right)$ and $V_0^i = E_0 \sum\limits_{t=0}^{\infty} \beta_i^t u\left(c_{i,t}, h_{i,t}, n_{i,t}\right)$ are the expected life-time utility functions of patient and impatient households, respectively. ζ_p and ζ_i denote the utility weights of each household; and Θ refers to the vector of policy parameters with respect to which the objective function is maximized. Problem (38) is subject to all the competitive equilibrium conditions of the extended model. As in Schmitt-Grohe and Uribe (2007), welfare gains of each agent type are defined as the implied permanent differences in consumption between two different scenarios. Formally, and for the case of patient households, consumption equivalent gains can be specified as a constant λ_p, that satisfies:

$$E_0 \sum_{t=0}^{\infty} \beta_p^t u\left(c_{p,t}^a, h_{p,t}^a, n_{p,t}^a, z_t^a\right) = E_0 \sum_{t=0}^{\infty} \beta_p^t u\left[\left(1+\lambda_p\right) c_{p,t}^b, h_{p,t}^b, n_{p,t}^b, z_t^b\right], \tag{39}$$

where superscripts a and b refer to the alternative CBDC policy scenario and the baseline case, respectively.

In order to assign values to ζ_p and ζ_i, we rely on two alternative but complementary criteria that are typically used in the literature. Welfare weighting criterion "A" solves problem (38) by further assuming that $\zeta_p = 0.5$ and $\zeta_i = 0.5$. That is, this criterion assigns the same weight to each of the two agent types.[37] Welfare criterion "B" goes one step further in treating both types of agents equally and solves (38) by assuming that $\zeta_p = (1-\beta_p)$ and $\zeta_i = (1-\beta_i)$. That ensures the

[37]Since the population weights of savers and borrowers are implicitly assumed to be identical, this criterion is equivalent to assuming a utilitarian social welfare function.

same utility weights across households discounting future utility at different rates.[38] For reporting purposes, welfare weights are normalized, $\widehat{\zeta}_x = \frac{(1-\beta_x)}{[(1-\beta_p)+(1-\beta_i)]}$, so that $\widehat{\zeta}_p + \widehat{\zeta}_i = 1$ also under welfare criterion "B".[39]

Figure 9 plots the individual and social welfare effects of changing the value of parameter ϕ_Y for quantity rules (i), (ii) and (iii), and welfare criteria "A" and "B", with $X_t = Y_t$, and $\phi_X = -5$, for the case of quantity rule (iii).[40] While there is a considerable range of positive ϕ_Y values for which both agent types are better-off with CBDC, figure 9 also shows that each type of household faces a different trade-off when being exposed to changes in ϕ_Y. The issuance of CBDC has three main effects on welfare. First, it satisfiesthe demand for a monetary instrument that provides patient households with liquidity services and for which there is no perfect substitute in the economy (i.e., liquidity services effect). This benefits primarily the savers. Second, it triggers a bank disintermediation effect on lending and output that operates through different channels as explained in section 3.3. This primarily affects negatively the welfare of the borrowers. Third, it induces a stabilizing effect on cash and bank deposits, ultimately leading to a smoothing of lending supply and, thus, of real economy variables such as consumption and housing. This positive stabilization effect is primarily beneficial for the borrowers and turns out to be larger the more countercyclical the policy rule is. This explains why the countercyclical quantity rule (iii) yields higher welfare than the acyclical (ii) or procyclical (iii) rule.

Overall, in the case of savers (i.e., CBDC holders), the liquidity services effect clearly dominates and, thus, welfare increases with the steady-state level of CBDC supply. In the case of borrowers (i.e., impatient households), up to a certain level, the stabilization effect dominates and issuing CBDC is welfare-improving also for those households who do not hold CBDC. Nonetheless, beyond a certain threshold - which depends on the specification of the CBDC quantity rule - the bank disintermediation effect starts to weigh comparatively more and higher values of ϕ_Y translate into lower levels of borrowers' welfare.

We numerically solve problem (38) for the two proposed welfare criteria by searching over the relevant grid of parameter values. For the cases of quantity rules (i) and (ii), the considered grid of parameter values is ϕ_Y {0.00 - 0.40} ; whereas for the case of quantity rule (iii) it is ϕ_Y {0.00 - 0.40}; ϕ_x {(-5.00) - 0.00}. Table 9 reports the corresponding optimized parameter values and the welfare gains.[41] Since the liquidity services effect is quantitatively the most important one, welfare gains

[38]This is a welfare weighting criterion typically considered in the macro-banking literature to prevent an over-weight of savers' welfare related to a higher discount factor (see, e.g., Lambertini et al. 2013; Alpanda and Zubairy 2017; Muñoz 2021.

[39]Under the baseline calibration this normalization implies that $\widehat{\zeta}_s = 0.2593$ and $\widehat{\zeta}_b = 0.7407$.

[40]Note that under this calibration of quantity rule (iii), CBDC supply adjusts in a countercyclical manner.

[41]In each case, the model is solved by using second-order perturbation techniques in Dynare. Unconditional lifetime utility is computed as the theoretical mean based on first order terms of the second-order approximation to

attained by savers (i.e., CBDC holders) under optimal CBDC quantity rules are significantly larger than those attained by borrowers. Not surprisingly, under welfare criterion B, optimal quantity rules are associated to comparatively lower amounts of CBDC in circulation. This welfare criterion implicitly weighs the bank disintermediation effect more heavily.

The same analysis is carried out for the interest rate rules. Figure 10 plots the individual and social welfare effects of changing the value of parameter ϕ_r for interest rate rules (i), (ii) and (iii) under welfare criteria "A" and "B" whereas Table 10 reports the corresponding optimized parameter values and the welfare gains.[42] Due to its countercyclical responsiveness through equation (24), for any CBDC-to GDP ratio, interest rate rule (iii) yields larger welfare gains than interest rate rule (ii), which is static. In addition, for any given CBDC-to-GDP ratio, the welfare gains attainable under optimal interest rate rules are larger than those which can be reached under optimal quantity rules. This is due to the larger stabilization effect. Under interest rate rules (and as opposed to quantity rules), the bulk of the adjustment in the CBDC market in response to exogenous shocks is made via quantities.[43]

Based on the same vector of CBDC issuance levels proposed in section 3.3, Figure 11 plots the percentage changes in the second-order approximation to the stochastic mean of liquidity services, z_t (panel A), the stochastic mean of quarterly real GDP (panel B), Y_t, and the stochastic standard deviation of bank lending (panel C),σ_L, that arise when the economy moves from the no CBDC scenario to each of the three considered CBDC policy scenarios. For any given steady state CBDC-to-GDP ratio, the impact on the levels of liquidity services and real GDP are roughly independent from the type of CBDC rule (panels A and B).[44] By way of contrast, the impact CBDC has on the volatility of bank lending (and, hence, on that of aggregates of the real economy) crucially depends on the type of CBDC rule. Panel C of Figure 11 confirms the main conclusions previously reached on the effects driving the differences in the welfare impacts under different types of CBDC rules. First, interest rate rules yield larger welfare gains than quantity rules. Second, due to their countercyclical nature, the smoothing effect under interest rate rule (iii) is larger than that induced under interest rate rule (ii). The same applies to quantity rule (iii), when being compared to quantity rules (ii) and (i), in this order. Third, the welfare maximizing quantity of CBDC in equilibrium increases with the size of the stabilization effect.

Figure 12 displays the impulse responses of selected aggregates to various supply, demand and

the nonlinear model, resulting in a second-order accurate welfare measure. This approach ensures that the effects of aggregate uncertainty are taken into account.

[42]Note that, under interest rate rule (i), there is no policy parameter with respect to which it can be optimized and welfare gains attained by each type of household are independent from the welfare criterion.

[43]Figure D.8 provides complementary information by displaying the main level and volatility effects that are behind the welfare effects induced by the three types of interest rate rules.

[44]The aim of reporting the corresponding percentage changes in GDP levels is to capture and synthesize the impact of CBDC on the real economy through the bank disintermediation effect.

financial shocks to provide further information on the size and workings of the stabilization effect. Liquidity services adjust in response to the exogenous shocks that hit this economy. Under any of the CBDC rules under consideration, part of this adjustment is borne by CBDC. This helps mitigating the response (and volatility) of cash and deposits, when compared to the baseline (no CBDC) scenario. Through this smoothing effect on deposits, CBDC stabilizes lending and housing services of borrowers, ultimately improving their welfare. The figure makes clear that for any given amount of CBDC in circulation (e.g., 30% of quarterly GDP), the size of the stabilization effect varies across types of CBDC rules.

Optimal Quantity of CBDC and Structural Bank Intermediation What does our model say about the optimal amount of CBDC in circulation and the structural (or steady state) impact of CBDC on bank valuations and lending to firms under the six (optimal) CBDC policy rules? Panel A of figure 13 displays the steady state CBDC interest rate-quantity vector, $\Xi = (r_{cbdc},\ CBDC)$, associated to each of the six different optimal CBDC policy rules.[45] Panel B shows the steady state impact the introduction of a CBDC has - under each CBDC policy rule - on the present value of banks as well as on bank lending to firms.[46] Three conclusions stand out as they are relevant for the current policy debate and are consistent with the empirical evidence presented in section 2. First, there is a high and positive correlation between the amount of CBDC in circulation and the structural impact of issuing a central bank digital currency on bank valuations and lending to firms. Second, by adequately calibrating the amount of CBDC in circulation (through an optimal policy rule), these effects can be significantly mitigated (see the difference between the magnitude of steady state effects on bank valuations and lending under the unconstrained CBDC supply scenario - i.e., interest rate rule (i) - and those under optimal CBDC policy rules). Third, regardless of the CBDC policy rule we look at, the optimal quantity of CBDC in equilibrium lies between 15% and 45% of quarterly real GDP. On 9 and 10 February 2021, ECB Board member Panetta reflected on the possibility of adopting a limit on individual CBDC holdings of EUR 3,000 which led to a trend reversal in the estimated impact of digital euro news on bank valuations and lending to firms (see section 2). If all citizens in the euro area were to hold this maximum individual level of CBDC in 2021, the amount of CBDC in circulation would be roughly 34% of quarterly GDP.[47] Based on euro area data for 2021, such an amount lies between 15% and 45% of quarterly real GDP.[48]

[45] Recall that, strictly speaking, interest rate rule (i) cannot be referred to as an optimal CBDC policy rule (since there is no policy parameter with respect to which it can be optimized), but rather as a CBDC policy scenario.

[46] Note that the choice of these two variables has been inspired by the two variables for which we present our empirical findings in section 2 (i.e., banks' market valuations and bank lending to firms). In our analysis, the present value of banks is proxied by the objective function of the representative bank.

[47] This number has been obtained after having rounded up the size of the population in the euro area to 340 million citizens and average quarterly GDP in 2021 to EUR 3,000 billions.

[48] In practice, the CBDC-to-GDP ratio under a EUR 3,000 limit on individual holdings would likely be lower than 34% and probably closer to the levels implied by optimal quantity rules (i.e., 15% - 30%) for at least two reasons.

In addition, the analysis further confirms that optimal CBDC interest rate rules are associated to a larger quantity of CBDC in equilibrium and, thus, to a more sizable bank disintermediation effect.

4.3 Robustness Checks

This section investigates the robustness of our findings on the optimal amount of CBDC in circulation to changes in key parameters. Table 11 reports the optimized policy parameter and the optimal quantity of CBDC (in parenthesis) corresponding to each of the six CBDC policy regimes (policy rules) for different values of key selected parameters.[49] Two important conclusions can be drawn from our analysis. First, everything else being equal, an increase in the magnitude of the bank disintermediation effect triggered by a change in any structural parameter lowers the optimal quantity of CBDC. Second, the range of values that we find for the optimal quantity of CBDC under the baseline calibration does not significantly change under ranges of structural parameter values that are considered to be of practical relevance.

In particular, we find that the optimal quantity of CBDC decreases with the degree of substitutability between CBDC and any of the other two forms of money. Therefore, the optimal amount of CBDC in circulation increases with the cash storage cost parameter, ψ_m, decreases with the preference weight parameter of deposits in the liquidity services aggregator (which can also be interpreted as a depositors' preference-driven proxy for banks'reliance on deposit funding) , ω_d, and declines with the elasticity of substitution across monetary instruments, η_z. Given that CBDC induces a bank disintermediation effect and $r_{cbdc} \leq 0$ for the policy scenarios under consideration, this finding makes clear that a central bank digital currency can only be welfare-improving as long as it provides individuals with certain (liquidity) services that are not facilitated by already existing forms of money. Furthermore, the optimal quantity of CBDC increases with the collateral requirement parameter, θ_b. A more stringent central bank collateral regulation amplifies the bank disintermediation effect by making central bank funding costlier to banks.

Of course, these shifts in the optimal quantity of CBDC directly depend on how the three welfare effects change. Figures D.10, D.11, D.12, and D.13 plot the individual and social welfare effects of changing the value of parameter ϕ_Y for quantity rule (i) and welfare criterion "B" under the same range of parameter values ψ_m, ω_d, η_z, and θ_b. For instance, an increase in ω_d leads to an amplification in: (i) the liquidity services effect, due to a lower degree of substitutability between bank deposits and other forms of money (panel A of figure D.11); (ii) the stabilization effect, as

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. See Adalid et al. (2022).

[49] Without loss of generality, the results in Table 11 are reported for the case of welfare weighting criterion "B" and for ranges of parameter values that are considered to be of practical relevance.

deposit holdings and credit supply become larger; and (iii) the bank disintermediation effect, due to a lower degree of substitutability between CBDC and deposits. Due to the latter, the welfare trade-off faced by borrowers - and by the society as a whole - worsens (panels B and C of figure D.11). That is, the optimal quantity of CBDC in equilibrium decreases with the relative preference for deposits and, thus, with banks' reliance on deposit funding.

5 Conclusion

The recent and growing literature on central bank digital currencies identifies a trade-off between the benefits of having access to a digital currency issued by a central bank for retail payment purposes and the potential risk of bank disintermediation through deposit substitution. We present novel evidence on bank stock price reactions to CBDC news in the euro area suggesting that market participants expect the impact of introducing a CBDC on the banks' valuations and lending conditions to crucially depend on the design features aimed at controlling the amount of central bank digital currency in circulation as well as on their reliance on deposit funding.

Against this background, we develop a quantitative macro-banking DSGE model that incorporates these trade-offs and the key mechanisms through which the issuance of a CBDC can potentially affect bank intermediation and the real economy. The imperfect substitutability across monetary instruments and various regulatory requirements, including minimum reserves, the central bank collateral framework and capital regulation, constitute channels that interact with one another and play a key role in the transmission of CBDC-induced effects to the banking sector and the macroeconomy.

Welfare-maximizing CBDC policy rules are effective in mitigating the risk of bank disintermediation and induce significant welfare gains for both, patient households (i.e., CBDC holders) and impatient households (i.e., borrowers who do not hold CBDC). Based on a social welfare maximization approach, the model suggests that the optimal amount of CBDC in circulation for the case of the euro area would lie between 15% and 45% of quarterly real GDP in equilibrium. In line with what our empirical analysis suggests, if CBDC were to be issued under no quantity limits and no remuneration, the amount of CBDC in circulation would be larger (i.e., of roughly 65% of quarterly real GDP) and the steady state effects on banks' valuations and lending would be comparatively more sizable. The main findings of our quantitative analysis are notably robust across different CBDC policy scenarios, welfare criteria and parameterizations of the model.

The simplicity of the model is instrumental to clearly identify the effects of issuing CBDC and the mechanisms through which they are transmitted. Yet, it comes at the cost of omitting ingredients which are present in reality and that could possibly change some of the results. The model could be extended along different dimensions so as to allow for a more accurate quantification of the impact issuing a certain amount of CBDC could have on bank intermediation.

On the one hand, there are assumptions of the model which could possibly be leading to an overstatement of the potential risk of bank disintermediation. Among others, the design of the central bank's collateral requirement (which only considers public debt as eligible asset) and the implicit assumption that it is always binding in a neighborhood of the steady state; the simplifying assumption according to which banks do not obtain revenues from offering CBDC-related services; the absence of other digital currencies and payment methods that would in practice compete with a CBDC in the segment of retail payments; and the omission of a more explicit modelling of some of the unconventional monetary policy measures which had contributed to the build-up of a large stock of excess reserves in the system of many advanced economies, a channel through which a larger proportion of the adjustment could take place in practice.

On the other hand, there are other assumptions due to which the model could be underestimating the impact of introducing a CBDC on the banking sector and the macroeconomy. First, the simple specification of the liquidity (reserves) requirement implies that, in practice, banks are likely to be more limited when deciding how to rebalance the asset and liabilities sides of their balance sheets in the face of a CBDC issuance. Second, the fiscal expansion effect could in practice be of a different nature and order of magnitude, not having the impact on private consumption and real GDP that the model predicts.

Finally, the tractability of the model allows for a more detailed and extended inspection of the interactions between CBDC policy and other related policies and regulations (e.g., monetary policy and the associated collateral framework, fiscal policy, capital and liquidity regulation).

References

Abad, J., Nuño, G., and Thomas, C. (2023). Implications of central bank digital currency for the operational framework of monetary policy. Unpublished working paper.

Adalid, R., Álvarez-Blázquez, A., Assenmacher, K., Burlon, L., Dimou, M., López-Quiles, C., Martín Fuentes, N., Meller, B., Muñoz, M. A., and Radulova, P. (2022). Central bank digital currency and bank intermediation. Occasional Paper 293, European Central Bank.

Agur, I., Ari, A., and Dell'Ariccia, G. (2022). Designing central bank digital currencies. *Journal of Monetary Economics*, 125(C):62–79.

Ahnert, T., Assenmacher, K., Hoffmann, P., Leonello, A., Monnet, C., and Porcellacchia, D. (2022). The economics of central bank digital currency. Working Paper 2713, European Central Bank.

Alpanda, S. and Zubairy, S. (2017). Addressing household indebtedness: Monetary, fiscal or macroprudential policy? *European Economic Review*, 92:47–73.

Andolfatto, D. (2021). Assessing the impact of central bank digital currency on private banks. *The Economic Journal*, 131(634):525–540.

Assenmacher, K., Berentsen, A., Brand, C., and Lamersdorf, N. (2021). A unified framework for CBDC design: remuneration, collateral haircuts and quantity constraints. Working Paper 2578, European Central Bank.

Assenmacher, K., Bitter, L., and Ristiniemi, A. (2023). CBDC and business cycle dynamics in a New Monetarist New Keynesian Model. Unpublished working paper.

Auer, R., Cornelli, G., Frost, J., et al. (2020). Covid-19, cash, and the future of payments. BIS Bulletin 3, Bank for International Settlements.

Bacchetta, P. and Perazzi, E. (2021). CBDC as Imperfect Substitute for Bank Deposits: A Macroeconomic Perspective. Research Paper 21-81, Swiss Finance Institute.

Barrdear, J. and Kumhof, M. (2022). The macroeconomics of central bank digital currencies. *Journal of Economic Dynamics and Control*, 142(C).

Bianchi, F., Kind, T., and Kung, H. (2019). Threats to Central Bank Independence: High-Frequency Identification with Twitter. NBER Working Paper 26308, National Bureau of Economic Research.

Bianchi, J. and Mendoza, E. (2018). Optimal time-consistent macroprudential policy. *Journal of Political Economy*, 126(2):588 – 634.

Binder, J. J. (1998). The event study methodology since 1969. *Review of Quantitative Finance and Accounting*, 11(2):111–37.

Brunnermeier, M. K. and Koby, Y. (2018). The Reversal Interest Rate. Working Paper 25406, National Bureau of Economic Research.

Brunnermeier, M. K. and Niepelt, D. (2019). On the equivalence of private and public money. *Journal of Monetary Economics*, 106:27–41.

Calvo, G. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics*, 12(3):383–398.

Chiu, J., Davoodalhosseini, S. M. R., Jiang, J. H., and Zhu, Y. (2019). Bank market power and central bank digital currency: Theory and quantitative assessment. Staff Working Paper 2019-20, Bank of Canada.

Coenen, G., Karadi, P., Schmidt, S., and Warne, A. (2018). The New Area-Wide Model II: an extended version of the ECB's micro-founded model for forecasting and policy analysis with a financial sector. Working Paper 2200, European Central Bank.

Degryse, H., De Jonghe, O., Jakovljević, S., Mulier, K., and Schepens, G. (2019). Identifying credit supply shocks with bank-firm data: Methods and applications. *Journal of Financial Intermediation*, 40(C).

Diamond, D. W. and Dybvig, P. H. (1983). Bank runs, deposit insurance, and liquidity. *Journal of Political Economy*, 91(3):401–419.

Drechsler, I., Savov, A., and Schnabl, P. (2017). The deposits channel of monetary policy. *The Quarterly Journal of Economics*, 132(4):1819–1876.

Fama, E. F. and French, K. R. (1993). Common risk factors in the returns on stocks and bonds. *Journal of Financial Economics*, 33(1):3–56.

Feenstra, R. (1986). Functional equivalence between liquidity costs and the utility of money. *Journal of Monetary Economics*, 17(2):271–291.

Fernández-Villaverde, J., Sanches, D., Schilling, L., and Uhlig, H. (2021). Central bank digital currency: central banking for all? *Review of Economic Dynamics*, 41:225–242.

Ferrari Minesso, M., Mehl, A., and Stracca, L. (2022). Central bank digital currency in an open economy. *Journal of Monetary Economics*, 127(C):54–68.

Gerali, A., Neri, S., Sessa, L., and Signoretti, F. (2010). Credit and banking in a dsge model of the euro area. *Journal of Money, Credit and Banking*, 42(s1):107–141.

Greenwood, J., Hercowitz, Z., and Huffman, G. (1988). Investment, capacity utilization, and the real business cycle. *American Economic Review*, 78(3):402–17.

Iacoviello, M. (2005). House prices, borrowing constraints, and monetary policy in the business cycle. *American Economic Review*, 95(3):739–764.

Iacoviello, M. (2015). Financial business cycles. *Review of Economic Dynamics*, 18(1):140–164.

Infante, S., Kim, K., Orlik, A., Silva, A. F., and Tetlow, R. J. (2022). The Macroeconomic Implications of CBDC: A Review of the Literature. Finance and economics discussion series 2022-07, Washington: Board of Governors of the Federal ReserveSystem.

Keister, T. and Monnet, C. (2022). Central bank digital currency: Stability and information. *Journal of Economic Dynamics and Control*, 142:104501.

Keister, T. and Sanches, D. (2022). Should Central Banks Issue Digital Currency? *The Review of Economic Studies*.

Khwaja, A. I. and Mian, A. (2008). Tracing the Impact of Bank Liquidity Shocks: Evidence from an Emerging Market. *American Economic Review*, 98(4):1413–1442.

Kiyotaki, N. and Moore, J. (1997). Credit cycles. *Journal of Political Economy*, 105(2):211–248.

Kumhof, M., Pinchetti, M., Rungcharoenkitkul, P., and Sokol, A. (2023). CBDC Policies in Open Economies. Working paper, Bank of England, forthcoming.

Lagos, R. and Wright, R. (2005). A Unified Framework for Monetary Theory and Policy Analysis. *Journal of Political Economy*, 113(3):463–484.

Lambertini, L., Mendicino, C., and Teresa Punzi, M. (2013). Leaning against boom–bust cycles in credit and housing prices. *Journal of Economic Dynamics and Control*, 37(8):1500–1522.

MacKinlay, A. C. (1997). Event studies in economics and finance. *Journal of Economic Literature*, 35(1):13–39.

Muñoz, M. A. (2021). Rethinking capital regulation: The case for a dividend prudential target. *International Journal of Central Banking*, 17(3):271–336.

Muñoz, M. A. and Soons, O. (2023). Public Money as a Store of Value, Heterogeneous Beliefs and Banks: Implications of CBDC. Working paper, European Central Bank, forthcoming.

Niepelt, D. (2020). Reserves for all? central bank digital currency, deposits, and their (non)-equivalence. *International Journal of Central Banking*.

Niepelt, D. (2022). Money and Banking with Reserves and CBDC. Discussion Paper 22-12, University of Bern, Department of Economics.

Piazzesi, M. and Schneider, M. (2022). Credit lines, bank deposits or CBDC? Competition and efficiency in modern payment systems. Unpublished working paper.

Schiller, J. and Gross, J. (2021). A Model for Central Bank Digital Currencies: Implications for Bank Funding and Monetary Policy. Conference Paper, VfS Annual Conference 2021: Climate Economics, Verein für Socialpolitik / German Economic Association.

Schilling, L., Fernández-Villaverde, J., and Uhlig, H. (2020). Central bank digital currency: When price and bank stability collide. Working Paper 28237, National Bureau of Economic Research.

Schmitt-Grohe, S. and Uribe, M. (2007). Optimal simple and implementable monetary and fiscal rules. *Journal of Monetary Economics*, 54(6):1702–1725.

Sefcik, S. and Thompson, R. (1986). An Approach To Statistical-Inference In Cross-Sectional Models With Security Abnormal Returns As Dependent Variable. *Journal of Accounting Research*, 24(2):316–334.

Sidrauski, M. (1967). Inflation and Economic Growth. *Journal of Political Economy*, 75:796–796.

Smets, F. and Wouters, R. (2003). An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area. *Journal of the European Economic Association*, 1(5):1123–1175.

Williamson, S. (2022a). Central Bank Digital Currency: Welfare and Policy Implications. *Journal of Political Economy*, 130(11):2829–2861.

Williamson, S. D. (2022b). Central bank digital currency and flight to safety. *Journal of Economic Dynamics and Control*, 142(C).

Wu, Y. (2018). What's behind Smooth Dividends? Evidence from Structural Estimation. *Review of Financial Studies*, 31(10):3979–4016.

Table 1: Determinants of abnormal stock market returns during digital euro events

	(1)	(2)	(3)	(4)	(5)	(6)
Deposit ratio	-0.057**	-0.050*	-0.054*	-0.058*	-0.077**	-0.081*
	(0.027)	(0.028)	(0.028)	(0.032)	(0.038)	(0.047)
Assets		1.463	1.316	1.305	-0.298	-1.475
		(0.942)	(0.957)	(0.954)	(0.948)	(1.164)
Reliance on TLTROs			-0.016	-0.020	0.003	-0.001
			(0.038)	(0.041)	(0.043)	(0.058)
Securities holdings			-0.013	-0.016	0.019	0.080
			(0.046)	(0.048)	(0.067)	(0.088)
Excess liquidity holdings			0.014	0.014	0.020	0.048
			(0.025)	(0.026)	(0.029)	(0.038)
ROA			-0.060	-0.043	-0.070	-0.122
			(0.100)	(0.099)	(0.106)	(0.141)
NPL ratio				-0.009		
				(0.025)		
CDS spread					0.003	0.001
					(0.002)	(0.002)
Event FE	YES	YES	YES	YES	YES	YES
Bank FE	YES	YES	YES	YES	YES	YES
Observations	1,601	1,601	1,601	1,601	1,146	1,146
R-squared	0.055	0.057	0.057	0.057	0.074	0.160

Notes: The specification is as in model (2). Dependent variable is bank-specific abnormal returns identified with the estimation of model (1). Observations are an unbalanced sample of 53 banks and 28 events. All controls are lagged by one month with respect to the month in which each event took place. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 2: Impact on lending from digital euro events

Dependent variable: Growth rate of loans	(1)	(2)	(3)	(4)	(5)
Reaction of stock prices	0.136**	0.355***	0.365***	0.290***	0.199*
	(0.063)	(0.054)	(0.058)	(0.052)	(0.106)
Assets	-3.155***	-3.106***	-3.003***	-2.365***	-2.311*
	(0.762)	(0.470)	(0.353)	(0.781)	(1.264)
Reliance on TLTROs		1.025***	1.041***	0.730*	1.322**
		(0.123)	(0.133)	(0.421)	(0.620)
Securities holdings		-0.400***	-0.422***	-0.537**	0.606**
		(0.139)	(0.141)	(0.224)	(0.285)
Excess liquidity holdings		0.288*	0.286**	0.134	-0.308
		(0.144)	(0.133)	(0.169)	(0.360)
ROA		3.583**	3.890***	4.417**	-4.490*
		(1.358)	(1.411)	(1.625)	(2.378)
NPL ratio			0.173		
			(0.175)		
CDS spread				0.038*	-0.048
				(0.022)	(0.036)
Industry - Location - Sector FE	YES	YES	YES	YES	-
Firm FE	-	-	-	-	YES
Observations	1,523,078	1,523,078	1,523,078	1,358,450	375,877
R-squared	0.110	0.112	0.112	0.120	0.454

Notes: The specification is as in model (3). Dependent variable is the percentage change in corporate loan volumes. Reaction of stock prices is the (cumulated) abnormal returns in October 2020. All controls are measured in September 2020. Standard errors clustered at the bank level in parentheses. *** p<0.01, ** p<0.05, *p<0.1.

Table 3: Baseline pre-set parameter values

Parameter	Description	Value
φ	Inverse of the Frisch elasticity	1.0000
σ_h	HH Risk aversion parameter	2.0000
ω_T	Fraction of taxes paid by HH_p	0.5000
δ_0^k	Depreciation rate of physical capital	0.0250
$\delta_1^k; \delta_2^k$	Endogenous depreciation rate params	$r_{k_e}^{ss}; 0.1\text{x}r_{k_e}^{ss}$
m_H	LTV ratio on HH housing	0.7000
$\gamma_{\widetilde{R}}$	Debt-to-assets, reserves risk-adjusted	1.0000
γ_b	Debt-to-assets, gov. bonds risk-adjusted	1.0000
ε	Elast. of subst. intermediate goods	6.0000
θ	Calvo probability	0.8200
χ_π	Inflation indexation parameter	0.2300
ρ_r	Taylor rule: smoothing parameter	0.9000
α_π	Taylor rule: inflation response param	2.5000
α_y	Tayor rule: GDP growth response param	0.1000

Notes: Parameters are set to standard values in the literature. Abbreviations HH, HHp and LTV refer to households, patient households and loan-to-value, respectively.

Table 4: Baseline calibrated parameter values: Part I

Parameter	Description	Value	Target ratio
β_p	Savers' discount factor	0.9930	$R_d^{ss} = (1.023)^{1/4}$
β_i	Borrowers' discount factor	0.9800	$(r_{le}^{ss} - r_d^{ss})x\ 400 = 3.0474$
j_p	Savers' housing services weight	0.0100	$C^{ss}/Y^{ss} = 0.5479$
j_i	Borrowers' housing services weight	8.7902	$l_i^{ss}/(Y^{ss}) = 1.9824$
χ_z	Savers' liquidity services weight	0.0541	$M^{ss}/Y^{ss} = 0.3326$
ω_d	Deposits weight in liquidity services	0.7100	$D^{ss}/A^{ss} = 0.8047$
η_z	Elast. of subst. liquidity services	3.5800	$(r_R^{ss} - r_d^{ss})x\ 400 = 0.2650$
ψ_m	Cash storage cost parameter	0.0020	$M^{ss}/F^{ss} = 0.5001$
m_K	LTV ratio on NFC physical capital	0.2140	$l_e^{ss}/A^{ss} = 0.3651$
α	Capital share in production	0.3300	$I^{ss}/Y^{ss} = 0.2124$
ν	Real estate share in production	0.0100	$l_e^{ss}/Y^{ss} = 1.6821$
γ_e	Debt-to-assets, NFC risk-adjusted	0.8950	$e^{ss}/l^{ss} = 0.1060$
γ_i	Debt-to-assets, HH risk-adjusted	0.9200	$l_i^{ss}/A^{ss} = 0.4303$
δ^e	Erosion rate of bank capital	0.0710	$\widetilde{R}_b^{ss}/A^{ss} = 0.0722$
θ_R	Banks' liquidity (reserves) requirement	0.0874	$\widetilde{R}_b^{ss}/Y^{ss} = 0.3326$
θ_b	Central bank funding collateral requirement	0.9950	$f^{ss}/A^{ss} = 0.0892$
ϕ_{Bp}	Fiscal rule: HH gov. bonds response param	0.4010	$b_b^{ss}//Y^{ss} = 0.6099$
ϕ_{Bb}	Fiscal rule: Banks' gov. bonds response param	0.2300	$b_b^{ss}//A^{ss} = 0.1324$
ϱ	Public consumption-to-GDP ratio	0.2070	$G^{ss}/Y^{ss} = 0.2070$
$\overline{\pi}$	Gross inflation target	1.0050	$(\pi - 1)x\ 400 = 2.0000$
μ	Lending-deposit facility corridor parameter	0.0059	$(r_f^{ss} - r_R^{ss})x\ 400 = 1.3860$
ϕ_Y	CBDC quantity rule: CBDC supply parameter	0.0000	$\widetilde{R}^{ss}/F^{ss} = 0.4999$

Notes: Parameters are calibrated to match steady state data targets. Abbreviations HH, NFC and LTV refer to households, non-financial corporations (entrepreneurial firms) and loan-to-value, respectively.

Table 5: Steady state ratios

Variable	Description	Model	Data
Bank statistics			
l_i^{ss}/Y^{ss}	HH loans-to-GDP ratio	2.0431	1.9824
l_e^{ss}/Y^{ss}	NFC loans-to-GDP ratio	1.7585	1.6820
b_b^{ss}/Y^{ss}	Bank government bonds-to-GDP ratio	0.6825	0.6099
l_i^{ss}/A^{ss}	HH loans-to-bank assets ratio	0.4243	0.4303
l_e^{ss}/A^{ss}	NFC loans-to-bank assets ratio	0.3652	0.3651
$\widetilde{R}_b^{ss}/A^{ss}$	Reserves-to-bank assets ratio	0.0671	0.0722
$b_b^{ss}//A^{ss}$	Bank government bonds-to-bank assets ratio	0.1417	0.1324
D^{ss}/A^{ss}	Deposits-to-bank assets ratio	0.7877	0.8047
f^{ss}/A^{ss}	Central bank funding-to-bank assets ratio	0.1400	0.0892
e^{ss}/l^{ss}	Equity-to-risk weighted assets ratio	0.0916	0.1060
Central bank statistics			
$\widetilde{R}^{ss}/Y^{ss}$	Reserves-to-GDP ratio	0.3315	0.3326
M^{ss}/Y^{ss}	Cash-to-GDP ratio	0.3428	0.3326
$\widetilde{R}^{ss}/F^{ss}$	Reserves-to-central bank assets ratio	0.4917	0.4999
M^{ss}/F^{ss}	Cash-to-central bank assets ratio	0.5083	0.5001
Macroeconomic statistics			
C^{ss}/Y^{ss}	Private consumption-to-GDP ratio	0.5549	0.5479
I^{ss}/Y^{ss}	Gross fixed capital formation-to-GDP ratio	0.2125	0.2124
G^{ss}/Y^{ss}	Public consumption-to-GDP ratio	0.2070	0.2070

Notes: Data targets have been constructed from euro area quarterly data for the period 2000:I-2021:II. The exception is the target for the bank capital-to-risk weighted assets, which has been based on the Basel III regime. Abbreviations HH, NFC refer to households, and non-financial corporations (entrepreneurial firms), respectively. Data sources are Eurostat and ECB.

Table 6: Steady state rates and spreads

Variable	Description	Model	Data
$(r_{le}^{ss} - r_d^{ss})x$ 400	Annualized Bank lending (to NFCs) spread	3.2316	3.0474
$(r_f^{ss} - r_R^{ss})x$ 400	Annualized lending-deposit facility corridor	2.3600	1.3860
$(r_R^{ss} - r_d^{ss})x$ 400	Annualized Reserves-deposits spread	0.2682	0.2650
$r_d^{ss}\ x$ 400	Annualized interest rate on bank deposits	2.2376	2.3000
$(\bar{\pi} - 1)\ x$ 400	Inflation target	2.0000	2.0000

Notes: Data targets for spreads and interest rates have been constructed from euro area quarterly data. While the period for which data targets for spreads have been constructed is 2000:I-2021:II, as standard in this strand of the macro-banking literature, the data target for the nominal interest rate on bank deposits is based on the pre-GFC period. The data target for the inflation target corresponds to the quantitative definition of the ECB's price stability objective. Abbreviation NFC refers to non-financial corporations (entrepreneurial firms). Data sources are Eurostat and ECB.

Table 7: Baseline calibrated parameter values: Part II

Parameter	Description	Value	Source/Target ratio
ψ_I	Investment adj. cost parameter	0.0920	$\sigma_I/\sigma_Y = 3.137$
σ	EIS dividends	6.4000	$\sigma_{\Omega_b}/\sigma_Y = 12.232$
σ_A	Std. productivity shock	0.0012	σ_Y x $100 = 2.631$
σ_h	Std. housing pref. shock	0.0090	σ_C / $\sigma_Y = 1.169$
σ_η	Std. elast. of subst. liquidity services shock	0.0012	σ_D / $\sigma_Y = 3.123$
σ_z	Std. liquidity pref. shock	0.0043	σ_M / $\sigma_Y = 3.408$
σ_{mh}	Std. HH collateral shock	0.0076	σ_L / $\sigma_Y = 3.138$
σ_{mk}	Std. NFC collateral shock	0.0237	$\sigma_e/\sigma_Y = 3.656$
σ_{θ_R}	Std. reserves requirement shock	0.1540	σ_R / $\sigma_Y = 15.011$
σ_{θ_b}	Std. Central bank funding collateral shock	0.0015	σ_F / $\sigma_Y = 6.375$
σ_r	Std. interest rate shock	0.00063	σ_{r_d} / $\sigma_Y = 0.043$

Notes: Parameters are calibrated to match second moment data targets. Abbreviations HH, NFC, EIS and Std refer to households, non-financial corporations (entrepreneurial firms), elasticity of intertemporal substitution and standard deviation, respectively.

Table 8: Second moments (relative volatilities)

Variable	Description	Model	Data
Bank statistics			
σ_{Ω_b} / σ_Y	Std. bank dividends/Std(GDP)	11.224	12.232
σ_L / σ_Y	Std.bank loans/Std(GDP)	2.596	3.138
σ_e / σ_Y	Std. bank capital/Std(GDP)	2.415	3.656
σ_D / σ_Y	Std. bank deposits/Std(GDP)	3.033	3.123
σ_{r_d} / σ_Y	Std. bank deposit interest rate/Std(GDP)	0.033	0.043
Central bank statistics			
σ_M / σ_Y	Std. banknotes/Std(GDP)	3.755	3.408
σ_R / σ_Y	Std. reserves/Std(GDP)	14.578	15.011
σ_F / σ_Y	Std. central bank assets/Std(GDP)	6.350	6.375
Macroeconomic statistics			
σ_I / σ_Y	Std. investment/Std(GDP)	2.542	3.137
σ_C / σ_Y	Std consumption/Std(GDP)	0.816	1.169
σ_Y x 100	Std(GDP) x 100	2.770	2.631

Notes: Series expressed in Euro amounts are seasonally adjusted and deflated, and their log value has been linearly detrended before computing standard deviation targets.These data targets have been constructed from euro area quarterly data for the period 2000:I-2021:II. For each variable, its relative volatility has been computed by dividing its standard deviation (Std) by the standard deviation of quarterly real GDP. The standard deviation of GDP is in quarterly percentage points. The standard deviation of bank dividends has been taken from the dataset used in Muñoz 2021.

Table 9: Welfare gains of optimal CBDC quantity rules

	Savers	Borrowers	Social
(A) Welf criterion "A" (i.e., $\zeta_{\varkappa} = 0.5$)			
(i) $\phi_Y^* = 0.236$	1.2377	0.0536	0.6457
(ii) $\phi_Y^* = 0.261$	1.3313	0.0572	0.6942
(iii) $\phi_Y^* = 0.262$; $\phi_X^* = -5$	1.3355	0.0652	0.7003
(B) Welf criterion "B" (i.e., $\zeta_{\varkappa} = 1 - \beta_{\varkappa}$)			
(i) $\phi_Y^* = 0.171$	0.9796	0.0613	0.2994
(ii) $\phi_Y^* = 0.189$	1.0533	0.0654	0.3216
(iii) $\phi_Y^* = 0.191$; $\phi_X^* = -5$	1.0618	0.0732	0.3295

Notes: Second-order approximation to the welfare gains associated to the optimal CBDC quantity rules and the corresponding optimized policy parameter for each of the two proposed welfare criteria. Welfare gains are expressed in percentage permanent consumption. Policy parameter values marked with an asterisk correspond to those for which social welfare is maximized under the corresponding welfare weighting criterion.

Table 10: Welfare gains of CBDC interest rate rules

	Savers	Borrowers	Social
(A) Welf criterion "A" (i.e., $\zeta_{\varkappa} = 0.5$)			
(i) $\phi_r = 0.000$	2.5587	0.0454	1.3020
(ii) $\phi_r^* = -0.385$	1.8460	0.0967	0.9714
(iii) $\phi_r^* = -0.453$	1.7526	0.1092	0.9309
(B) Welf criterion "B" (i.e., $\zeta_{\varkappa} = 1 - \beta_{\varkappa}$)			
(i) $\phi_r = 0.000$	2.5587	0.0454	0.6971
(ii) $\phi_r^* = -0.620$	1.5338	0.1058	0.4761
(iii) $\phi_r^* = -0.670$	1.4821	0.1171	0.4710

Notes: Second-order approximation to the welfare gains associated to the CBDC interest rate rules and the corresponding optimized policy parameter for each of the two proposed welfare criteria. Welfare gains are expressed in percentage permanent consumption. Policy parameter values marked with an asterisk correspond to those for which social welfare is maximized under the corresponding welfare weighting criterion.

Table 11: Robustness checks. Optimal policy parameter and optimal quantity of CBDC

	ϕ_Y *(i)*	ϕ_Y *(ii)*	ϕ_Y *(iii)*	ϕ_r *(i)*	ϕ_r *(ii)*	ϕ_r *(iii)*
(A) ψ_m						
(i) $\psi_m = 0.0005$	0.141	0.153	0.157	0.000	-0.734	-0.743
	(14.1%)	(15.3%)	(15.7%)	(58.1%)	(24.2%)	(24.0%)
(ii) $\psi_m = 0.001$	0.165	0.181	0.184	0.000	-0.621	-0.659
	(16.5%)	(18.1%)	(18.4%)	(61.0%)	(29.4%)	(28.2%)
(iii) $\psi_m = 0.002$	0.171	0.189	0.191	0.000	-0.620	-0.670
	(17.1%)	(18.9%)	(19.1%)	(64.4%)	(31.8%)	(30.2%)
(B) ω_d						
(i) $\omega_d = 0.65$	0.231	0.254	0.255	0.000	-0.578	-0.634
	(23.1%)	(25.5%)	(27.0%)	(72.1%)	(38.1%)	(36.0%)
(ii) $\omega_d = 0.71$	0.171	0.189	0.191	0.000	-0.620	-0.670
	(17.1%)	(18.9%)	(19.1%)	(64.4%)	(31.8%)	(30.2%)
(iii) $\omega_d = 0.75$	0.139	0.154	0.156	0.000	-0.578	-0.634
	(13.9%)	(15.4%)	(15.6%)	(59.6%)	(30.3%)	(28.5%)
(C) η_z						
(i) $\eta_z = 3.00$	0.217	0.237	0.238	0.000	-0.720	-0.776
	(21.7%)	(23.7%)	(23.8%)	(70.1%)	(34.9%)	(33.2%)
(ii) $\eta_z = 3.58$	0.171	0.189	0.191	0.000	-0.620	-0.670
	(17.1%)	(18.9%)	(19.1%)	(64.4%)	(31.8%)	(30.2%)
(iii) $\eta_z = 4.00$	0.141	0.158	0.160	0.000	-0.570	-0.615
	(14.1%)	(15.8%)	(16.0%)	(60.7%)	(29.6%)	(28.1%)
(D) θ_b						
(i) $\theta_b = 0.900$	0.136	0.150	0.153	0.000	-0.715	-0.733
	(13.6%)	(15.0%)	(15.3%)	(62.6%)	(26.1%)	(25.5%)
(ii) $\theta_b = 0.950$	0.155	0.170	0.173	0.000	-0.664	-0.699
	(15.5%)	(17.0%)	(17.3%)	(63.6%)	(29.1%)	(28.0%)
(iii) $\theta_b = 0.995$	0.171	0.189	0.191	0.000	-0.620	-0.670
	(17.1%)	(18.9%)	(19.1%)	(64.4%)	(31.8%)	(30.2%)

Notes: Second-order approximation to the welfare gains associated to the optimal CBDC quantity rules and the corresponding optimized policy parameter for each of the two proposed welfare criteria. Welfare gains are expressed in percentage permanent consumption. Policy parameter values marked with an asterisk correspond to those for which social welfare is maximized under the corresponding welfare weighting criterion. Optimized policy parameter and optimal quantity of CBDC (in parenthesis and expressed as a percent of quarterly real GDP) associated to the six different CBDC policy scenarios (rules) under welfare weighting criterion B and for different values of key selected parameters. When considering a change in the value of a key selected parameter, all other parameters of the model remain fixed to their baseline calibration values. For the case of quantity rule (iii), the value of the cyclical policy parameter is set to -5.

Figure 1: Overview of CBDC transmission

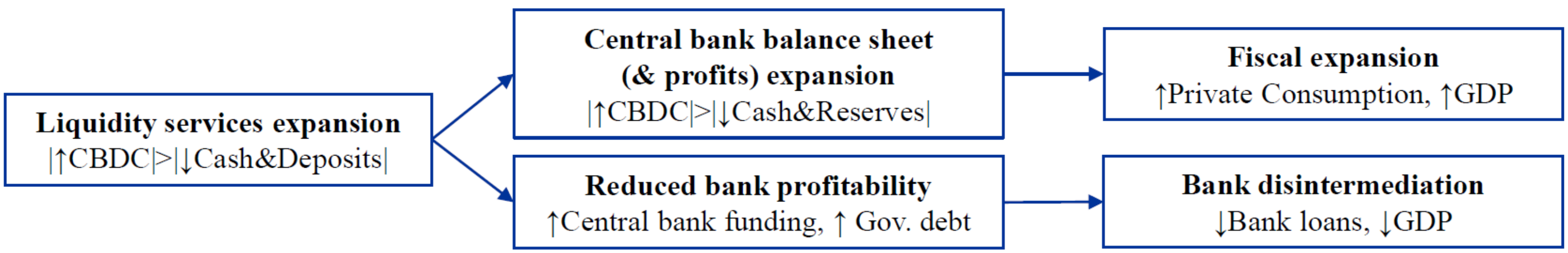
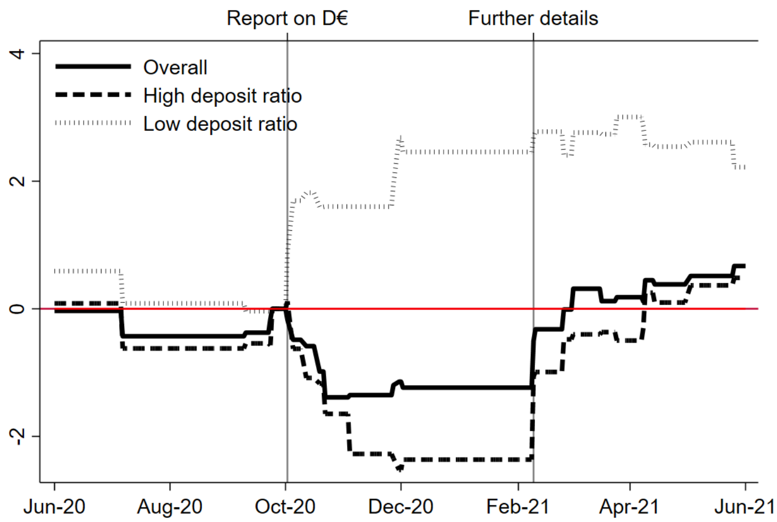
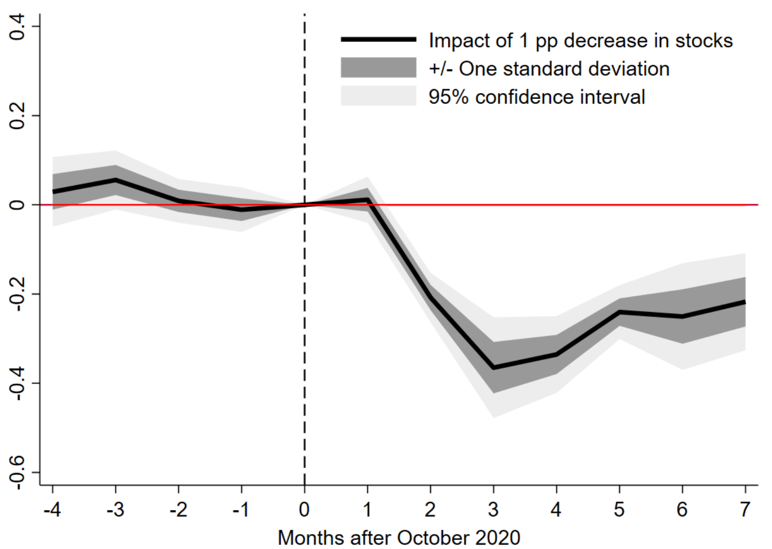


Figure 2: Stock market reactions to CBDC news by euro area banks (percentage points)



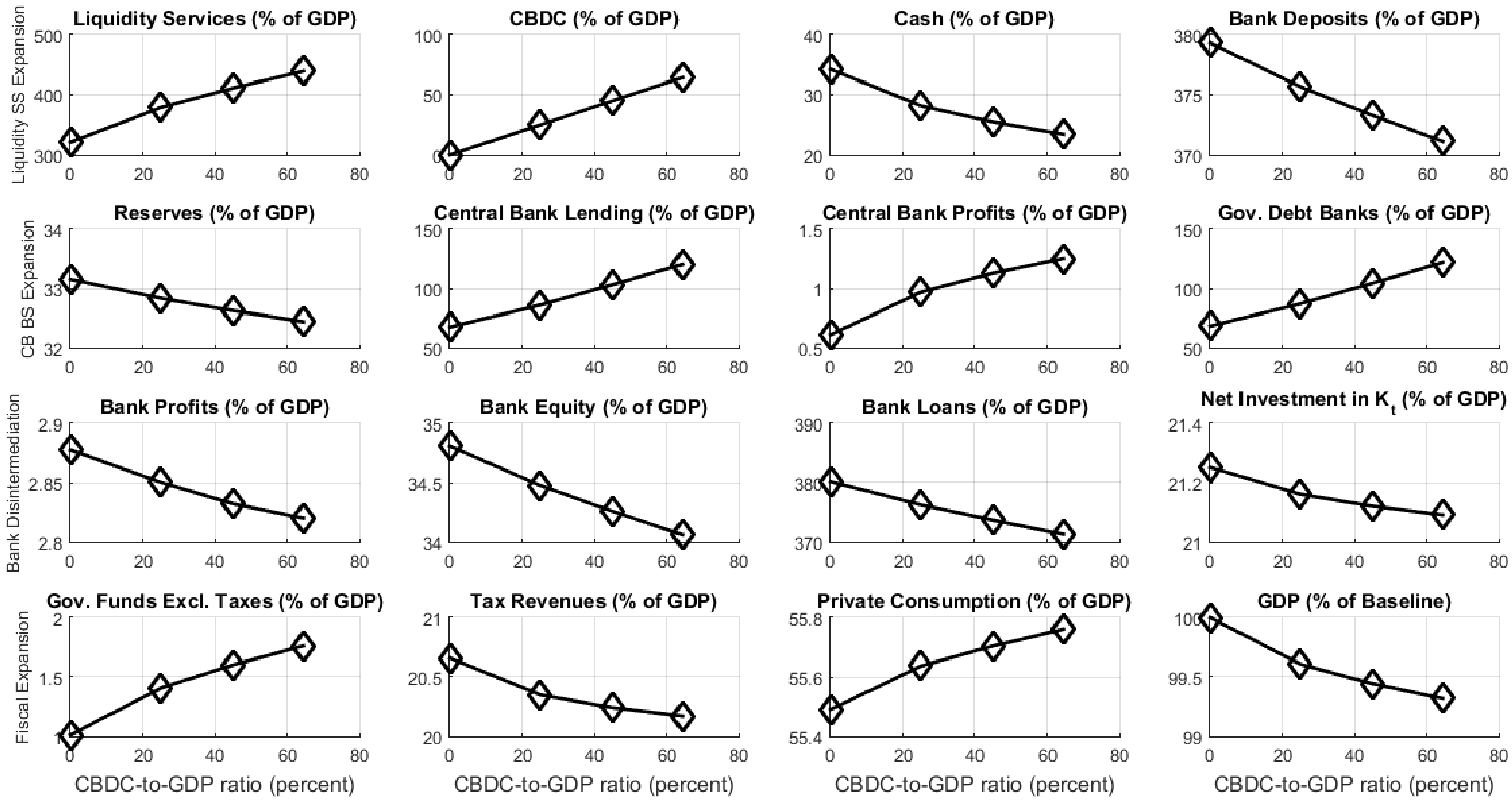
Notes: The figure reports the results of the estimation of model (1). Each horizontal segment reports the cumulated abnormal returns up to the latest key event, relative to the level on 1 October 2020. The solid line reports the average across all banks in the sample. The dashed and dotted lines report the average within two groups of banks, those with deposit ratio above or below the median, respectively. The two grey vertical lines indicate the publication of the ECB report on a digital euro on 2 October 2020 and the interview on 9 February 2021.

Figure 3: Change in loan volumes to firms associated with reactions of bank stock prices (percentages of volumes in October 2020)



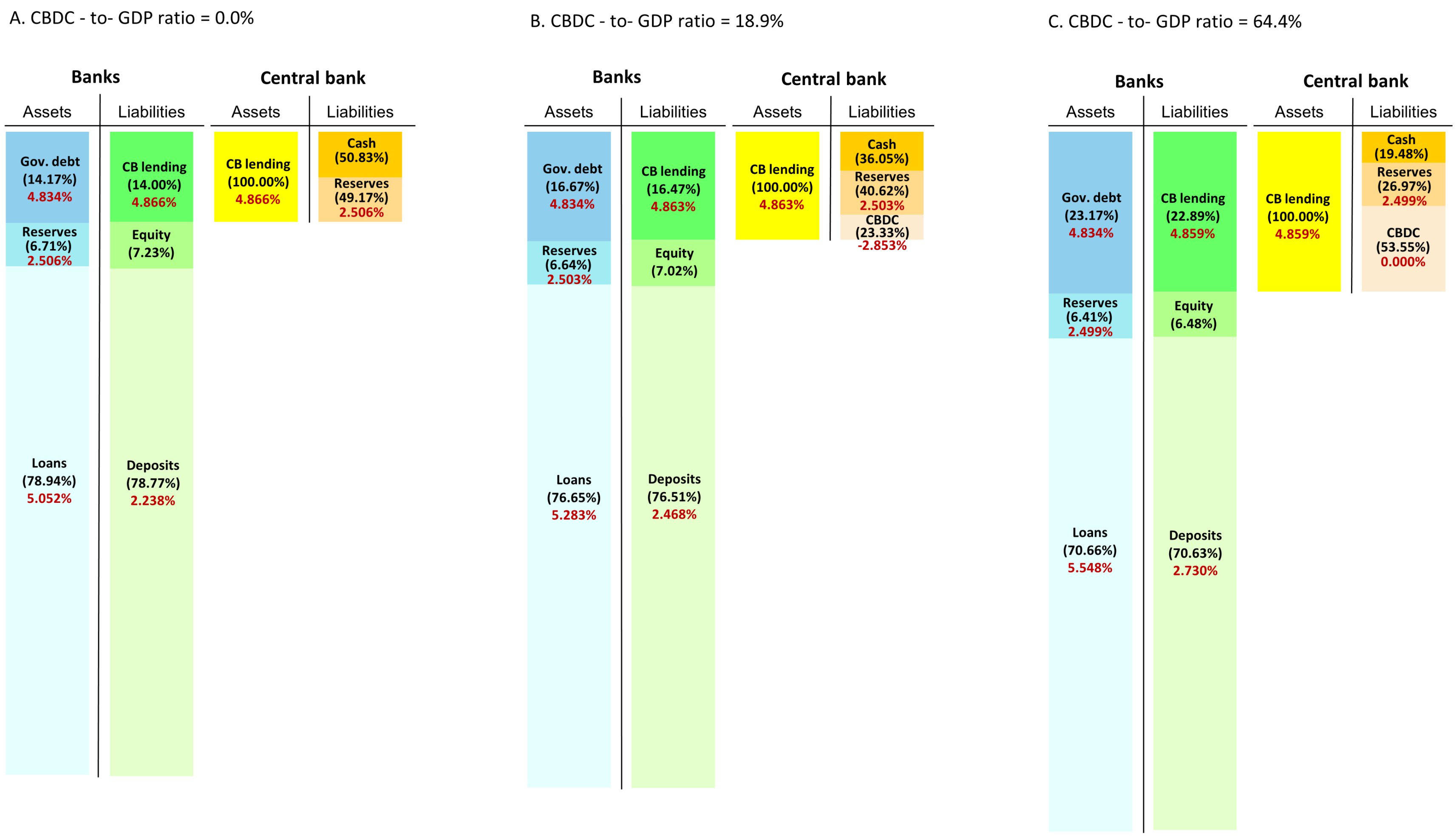
Notes: The figure reports the results of the estimation of model (3) with the specification of Table 2 (column 3). The solid line reports, for each monthly horizon from October 2020 indicated on the horizontal axis, the impact of 1 pp decrease in (cumulated) abnormal returns in October 2020. Shaded areas represent confidence intervals based on standard errors clustered at the bank level.

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



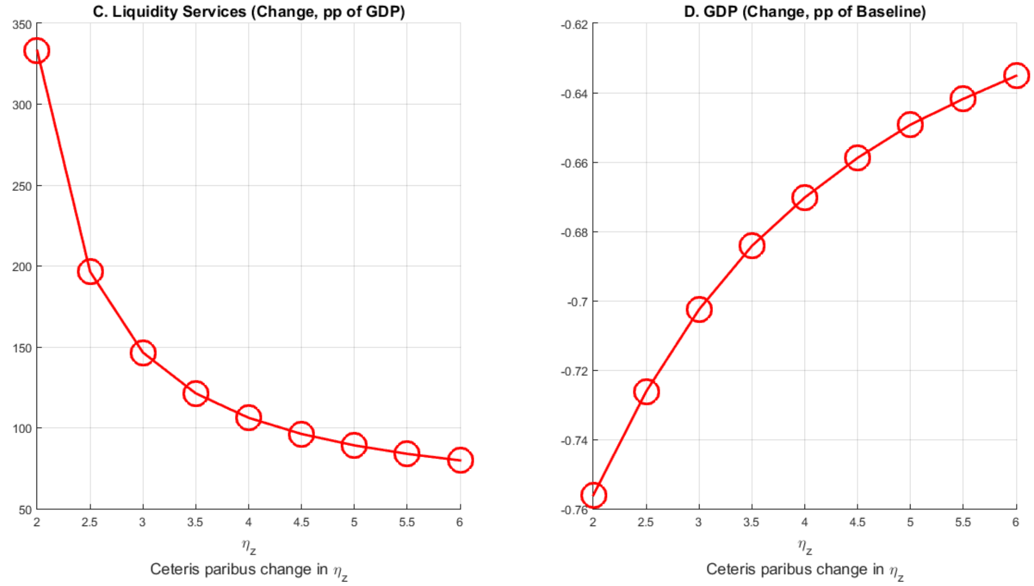
Notes: The figure reports the steady state level of key selected aggregates (expressed as a percent of quarterly GDP) under the baseline scenario as well as under alternative CBDC scenarios for which CBDC supply in equilibrium is assumed to be equal to 25%, 45% and 64.4% of quarterly real GDP, respectively. Government funds excluding taxes include central bank profits and the net issuance of public debt. Abbreviations SS and CB BS refer to services and central bank balance sheet, respectively.

Figure 5: Banks and central bank's balance sheets



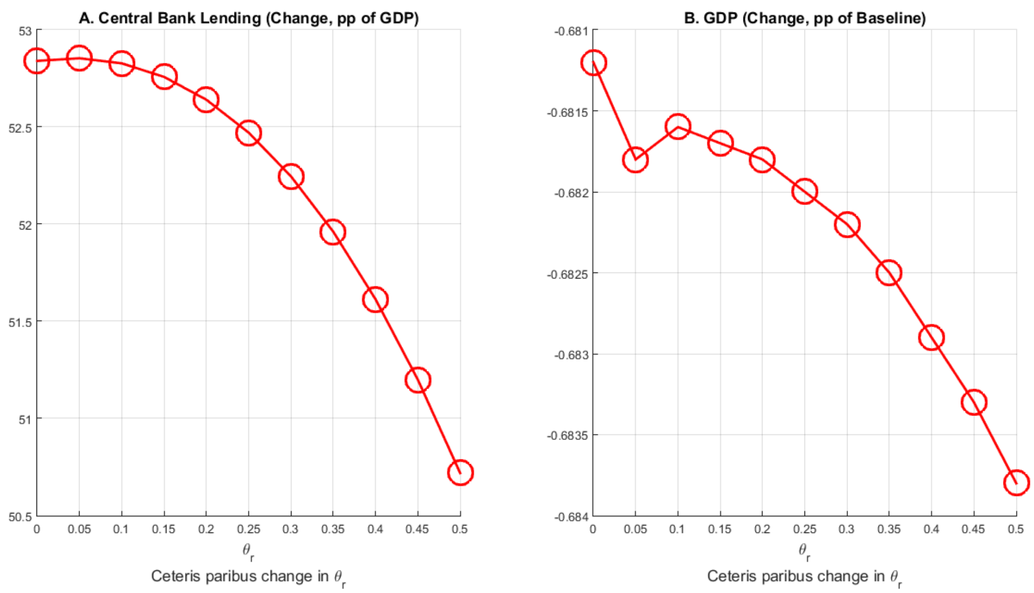
Notes: The figure illustrates how does the steady state composition (and related interest rates) of banks and central bank's balance sheets change in response to the issuance of a CBDC under scenarios in which CBDC is assumed to be equal to 18.9% (panel B) and 64.4% of quarterly real GD (panel C). As explained in section 4, the scenario illustrated in panel B corresponds to the optimal CBDC policy under a "quantity rule (ii)" type of CBDC regime (for welfare criterion "B"), whereas the scenario illustrated in panel C relates to the 0% CBDC interest rate scenario. For each balance sheet item, the black number in parenthesis refers to its share in total assets (in percent) whereas the red number makes reference to the corresponding annualized interest rate (in percentage points). Abbreviation CB refers to central bank.

Figure 6: Liquidity services expansion: η_z



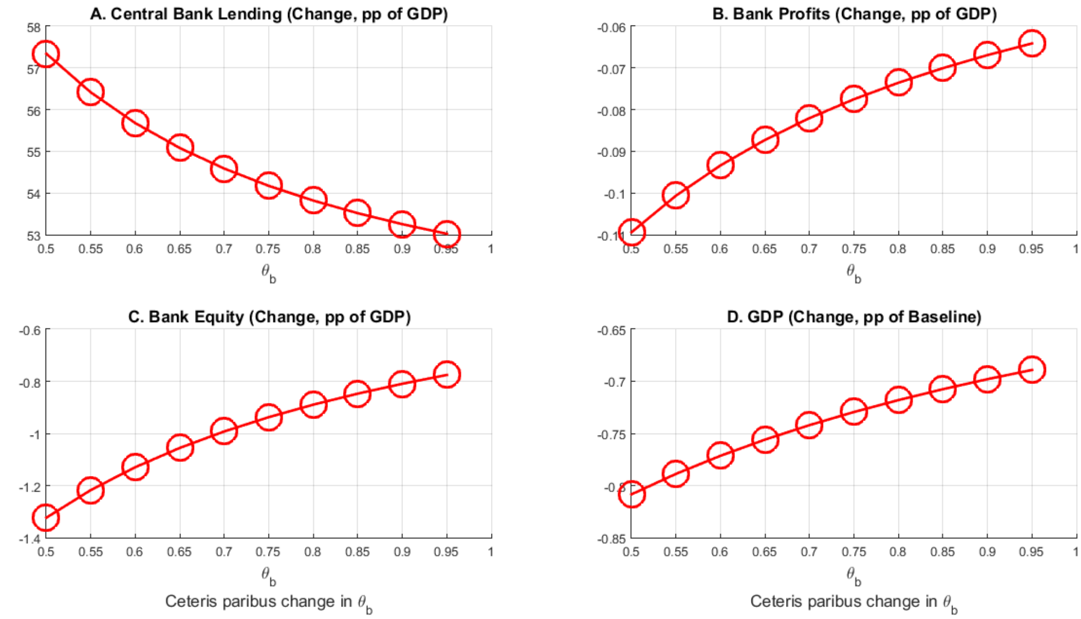
Notes: CBDC-induced changes in the steady state level of liquidity services (expressed in percentage points of GDP) and GDP (expressed in percentage points of its baseline level) - associated with the scenario under which CBDC supply in equilibrium is equal to 64.4% of quarterly GDP (i.e., zero CBDC interest rate) - for different values of the elasticity of substitution across monetary instruments, η_z.

Figure 7: Central bank balance sheet expansion: θ_r



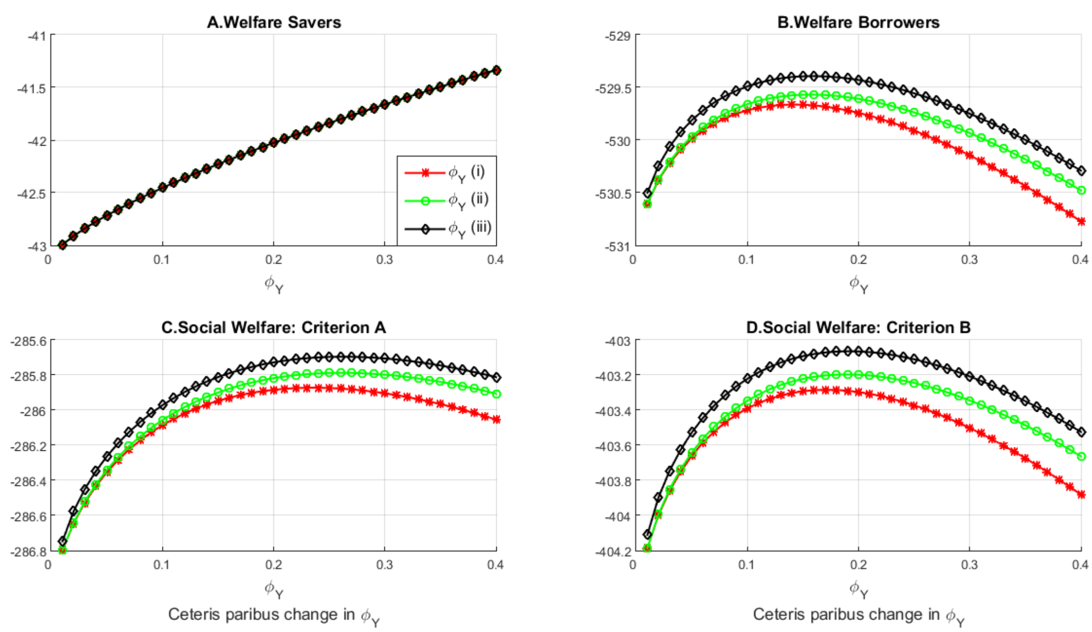
Notes: CBDC-induced changes in the steady state level of central bank lending (expressed in percentage points of GDP) and GDP (expressed in percentage points of its baseline level) - associated with the scenario under which CBDC supply in equilibrium is equal to 64.4% of quarterly GDP (i.e., zero CBDC interest rate) - for different values of the reserve requirements parameter, θ_r .

Figure 8: Bank disintermediation: θ_b



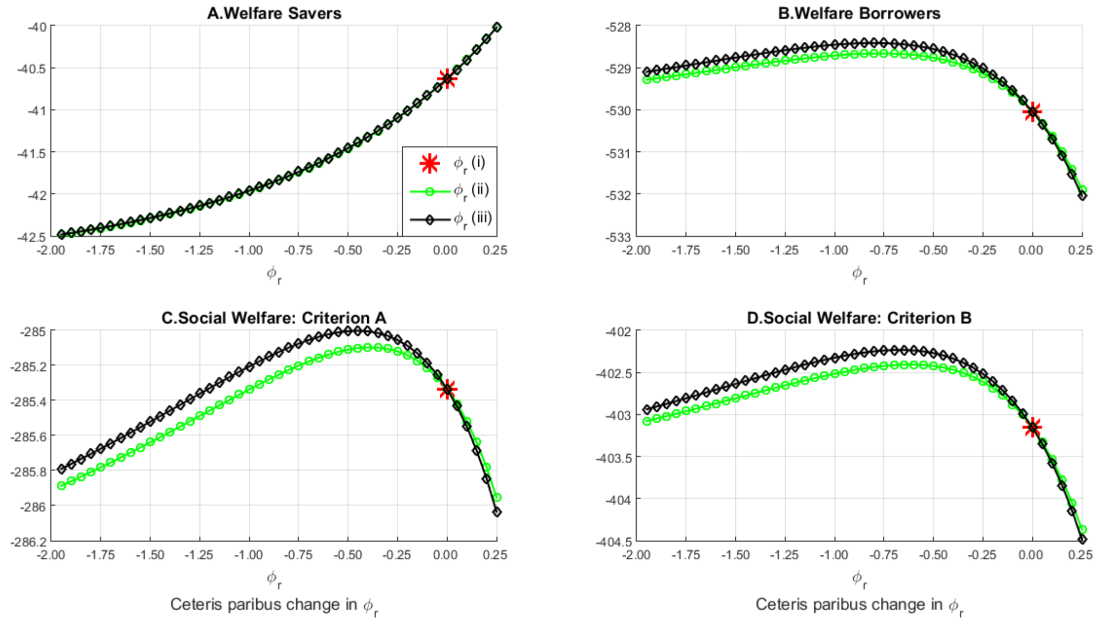
Notes: CBDC-induced changes in the steady state level of central bank lending, bank profits and equity (expressed in percentage points of GDP) as well as GDP (expressed in percentage points of its baseline level) - associated with the scenario under which CBDC supply in equilibrium is equal to 64.4% of quarterly GDP (i.e., zero CBDC interest rate) - for different values of central bank collateral requirement parameter θ_b.

Figure 9: Welfare effects of CBDC quantity rules (ceteris paribus changes in ϕ_Y)



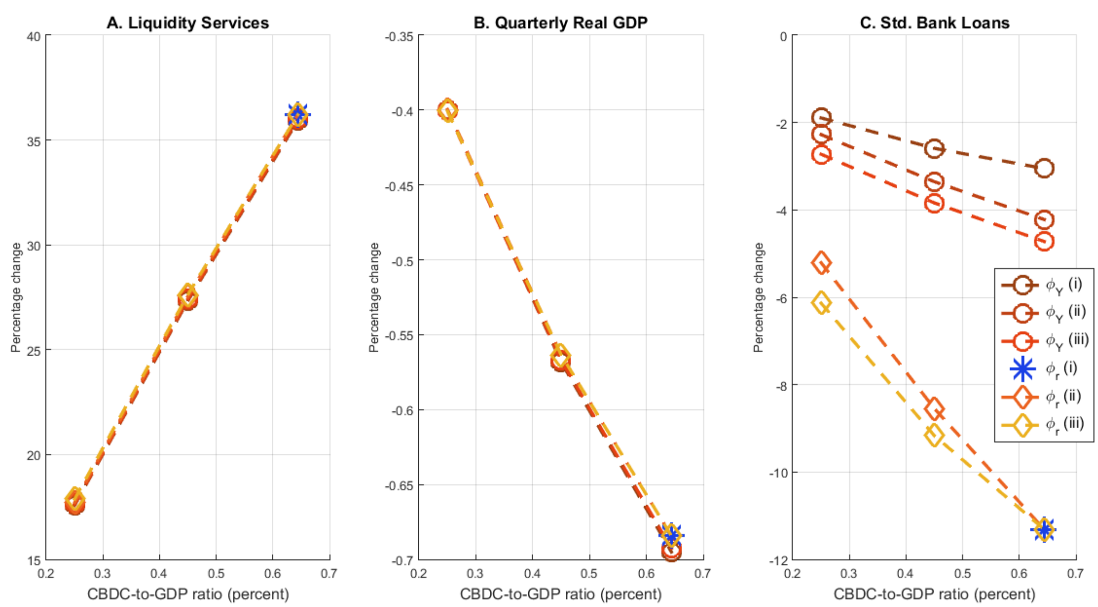
Notes: Second-order approximation to the unconditional welfare of savers and borrowers as well as to the unconditional social welfare under welfare criteria "A" and "B" as a function of CBDC policy parameter ϕ_Y. The starred line, the dotted line, and the diamond line relate to CBDC quantity rules (i), (ii) and (iii), respectively.

Figure 10: Welfare effects of CBDC interest rate rules (ceteris paribus changes in ϕ_r)



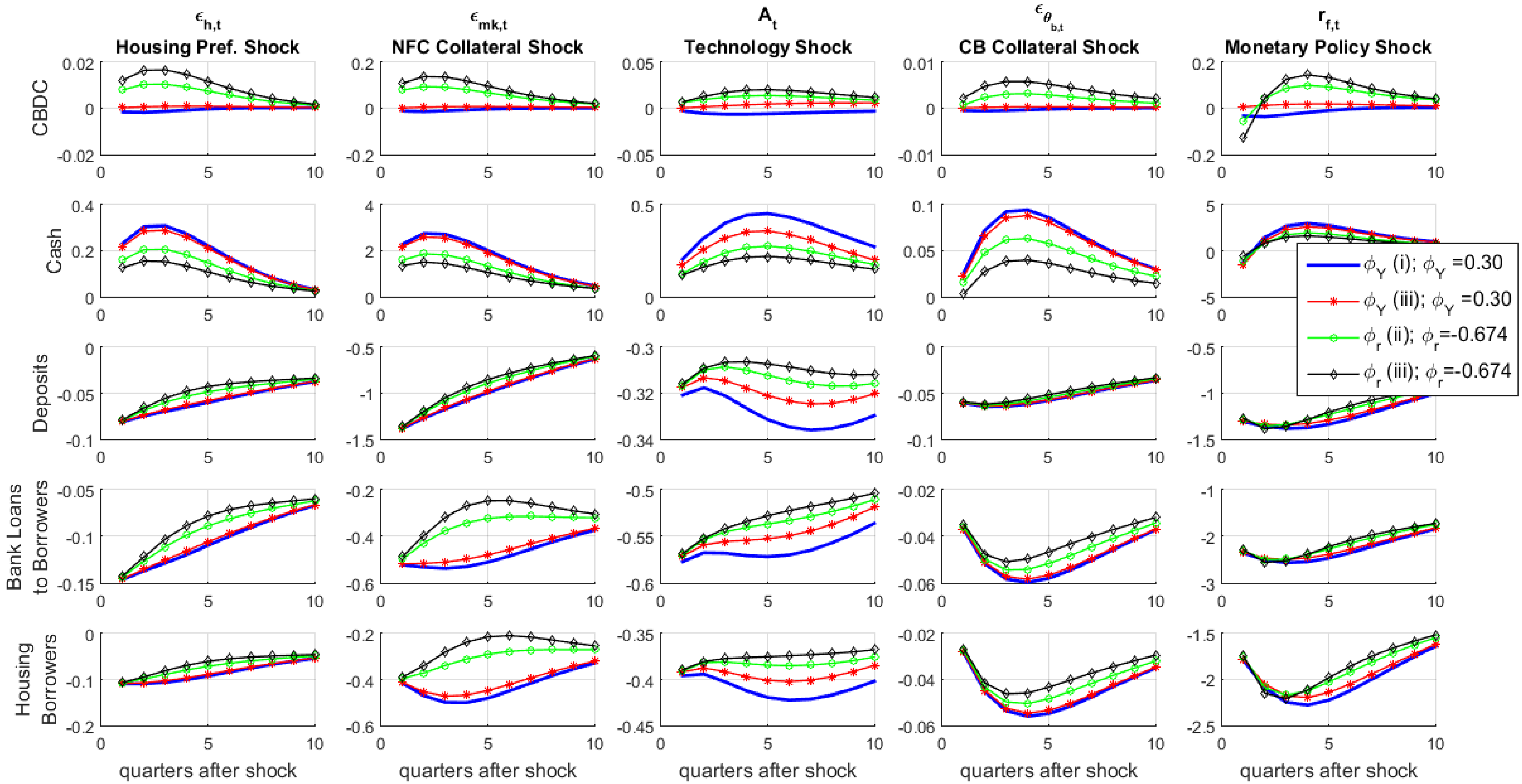
Notes: Second-order approximation to the unconditional welfare of savers and borrowers as well as to the unconditional social welfare under welfare criteria "A" and "B" as a function of CBDC policy parameter ϕ_r. The starred line, the dotted line, and the diamond line refer to CBDC interest rate rules (i), (ii) and (iii), respectively.

Figure 11: Liquidity services, bank disintermediation and stabilization effects



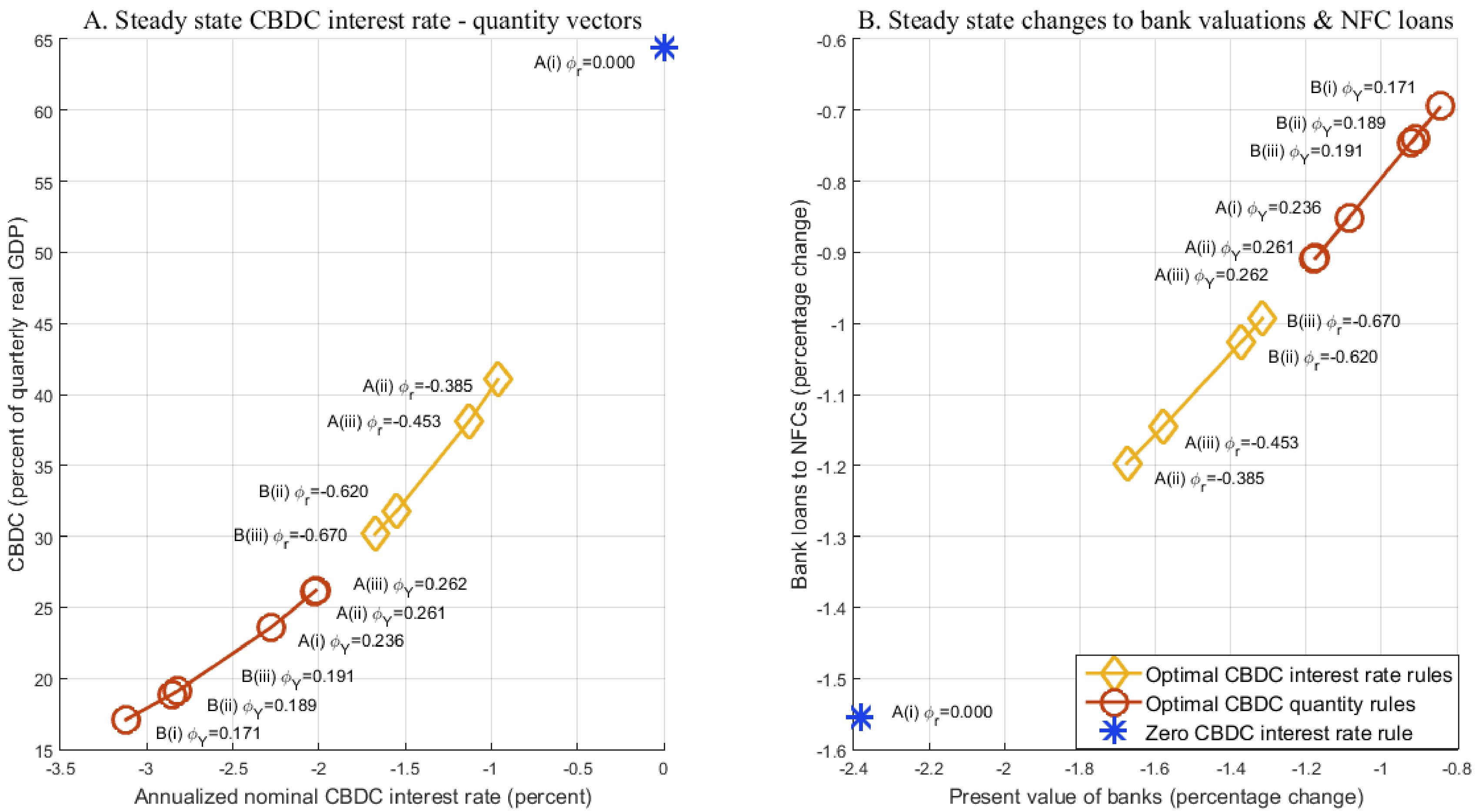
Notes: For each of the six considered specifications of the CBDC policy rule, the figure reports the percentage change in the second-order approximation to the stochastic mean of liquidity services (panel A), the stochastic mean of quarterly real GDP (panel B), and the stochastic standard deviation of bank lending (panel C) arising when the economy moves from the no CBDC scenario to alternative CBDC scenarios under which the quantity of CBDC in equilibrium is assumed to be equal to 25%, 45% and 64% of quarterly real GDP, respectively.

Figure 12: Stabilization effect: IRFs to different types of shocks



Notes: Variables are expressed in percentage deviations from the steady state with the exception of CBDC, which is shown as absolute deviations from the steady state. The solid, starred, dotted, and diamond lines refer to different CBDC regimes for which the corresponding CBDC rule has been calibrated such that the quantity of CBDC in equilibrium is equal to 30% of quarterly real GDP. For the case of quantity rule (iii), the value of the cyclical policy parameter is set to -5.

Figure 13: Optimal quantity of CBDC and steady state effects on banks



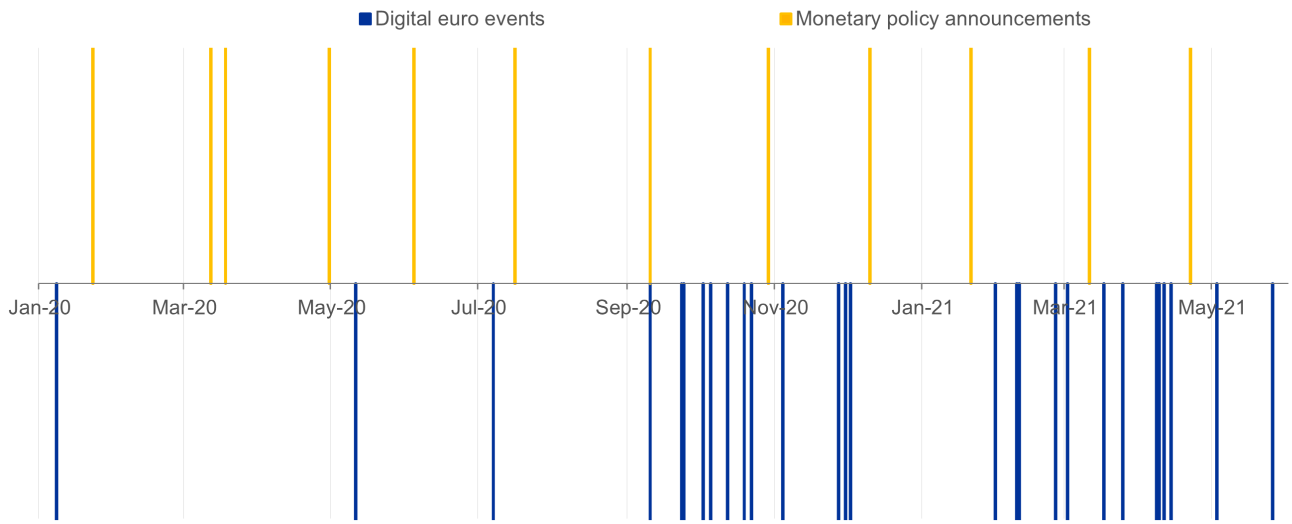
Notes: For each of the six considered specifications of the CBDC policy rule and for welfare weighting criteria "A" and "B", panel A reports the annualized nominal CBDC interest rate and the CBDC-to-real GDP ratio associated to each welfare-maximizing CBDC policy rule as well as to the zero CBDC interest rate regime (i.e., the unconstrained CBDC supply scenario). For the same CBDC policy scenarios, panel B displays the steady state impact on bank valuations and aggregate bank loans to firms. Bank valuations in the model are proxied by the recursive value of the representative bank (i.e., the objective function of banks' optimization problem).

A Additional Empirical Evidence

Table A.1: List of digital euro events

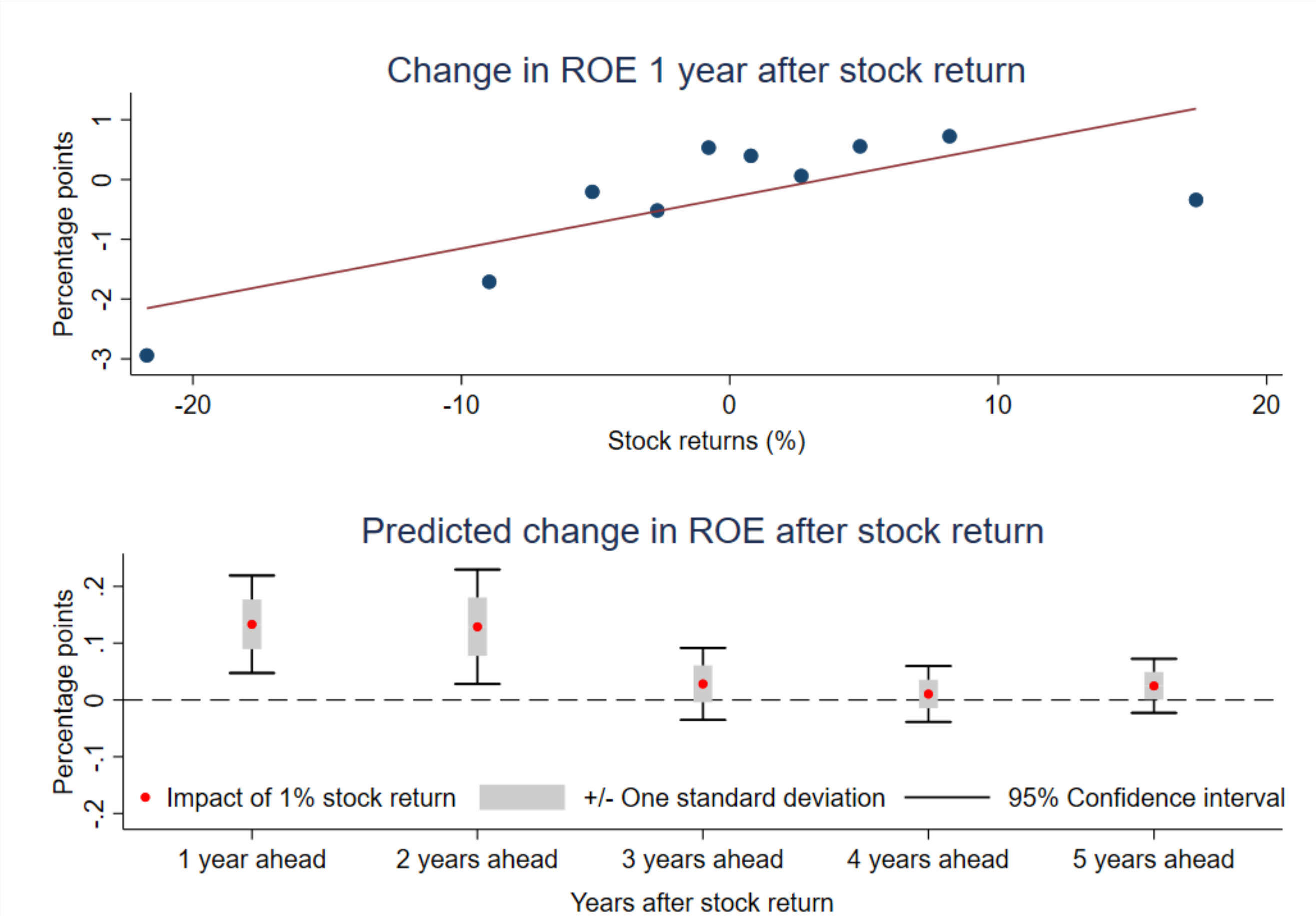
Date	Event	Subject	Type of event
08-Jan-20	INTERVIEW	Christine Lagarde: Interview with “Challenges” magazine	Neutral
11-May-20	SPEECH	Yves Mersch: An ECB digital currency – a flight of fancy?	Detailing D€
07-Jul-20	SPEECH	Fabio Panetta: Unleashing the euro’s untapped potential at global level	Neutral
10-Sep-20	SPEECH	Christine Lagarde: Payments in a digital world	Neutral
23-Sep-20	INTERVIEW	Yves Mersch: Interview with Bloomberg	Neutral
24-Sep-20	INTERVIEW	Philip R. Lane: Q&A on Twitter	Neutral
02-Oct-20	THE ECB BLOG	Fabio Panetta: We must be prepared to issue a digital euro	Fostering D€
02-Oct-20	PRESS RELEASE	ECB intensifies its work on a digital euro	Fostering D€
05-Oct-20	VOXEU COLUMN	Fabio Panetta & Ulrich Bindseil: CBDC remuneration in a world with low or negative nominal interest rates	Detailing D€
12-Oct-20	SPEECH	Fabio Panetta: A digital euro for the digital era	Fostering D€
19-Oct-20	INTERVIEW	Christine Lagarde: Interview with Le Monde	Neutral
22-Oct-20	SPEECH	Fabio Panetta: On the edge of a new frontier: European payments in the digital age	Neutral
04-Nov-20	SPEECH	Fabio Panetta: The two sides of the (stable)coin	Neutral
27-Nov-20	SPEECH	Fabio Panetta: From the payments revolution to the reinvention of money	Fostering D€
30-Nov-20	INTERVIEW	Christine Lagarde: The future of money – innovating while retaining trust	Fostering D€
02-Dec-20	THE ECB BLOG	Fabio Panetta: Money in the digital era	Neutral
31-Jan-21	INTERVIEW	Isabel Schnabel: Interview with Deutschlandfunk	Neutral
09-Feb-21	INTERVIEW	Fabio Panetta: Interview with Der Spiegel	Detailing D€
10-Feb-21	SPEECH	Fabio Panetta: Evolution or revolution? The impact of a digital euro on the financial system	Detailing D€
25-Feb-21	INTERVIEW	Isabel Schnabel: Interview with LETA	Detailing D€
02-Mar-21	INTERVIEW	Luis de Guindos: Interview with Público	Neutral
17-Mar-21	INTERVIEW	Frank Elderson: Q&A on Twitter	Neutral
25-Mar-21	THE ECB BLOG	Fabio Panetta: Digital central bank money for Europeans – getting ready for the future	Neutral
08-Apr-21	SPEECH	Christine Lagarde: IMFC Statement	Neutral
09-Apr-21	INTERVIEW	Isabel Schnabel: Interview with Der Spiegel	Detailing D€
11-Apr-21	INTERVIEW	Fabio Panetta: Interview with El País	Detailing D€
14-Apr-21	PRESS RELEASE	ECB publishes the results of the public consultation on a digital euro	Neutral
14-Apr-21	SPEECH	Fabio Panetta: A digital euro to meet the expectations of Europeans	Neutral
03-May-21	INTERVIEW	Luis de Guindos: Interview with La Repubblica	Neutral
26-May-21	INTERVIEW	Fabio Panetta: Interview with Nikkei	Detailing D€

Figure A.1: Sequence of digital euro events and monetary policy announcements



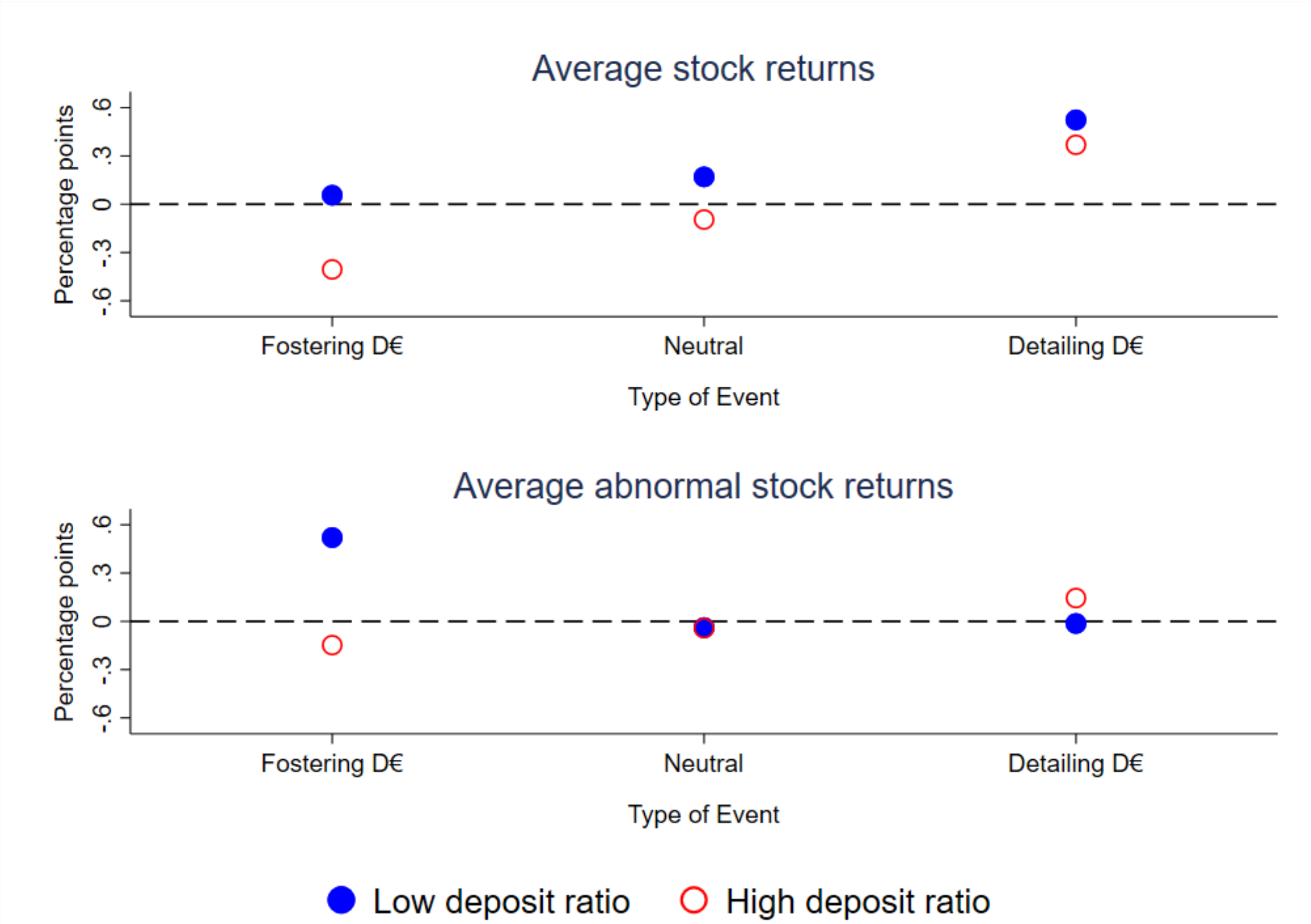
Notes: Blue lines indicate days corresponding to digital euro events as reported in Table A.1. Yellow lines indicate days corresponding to monetary policy announcements by the ECB.

Figure A.2: Historical correlation between bank stock market returns and subsequent bank profits



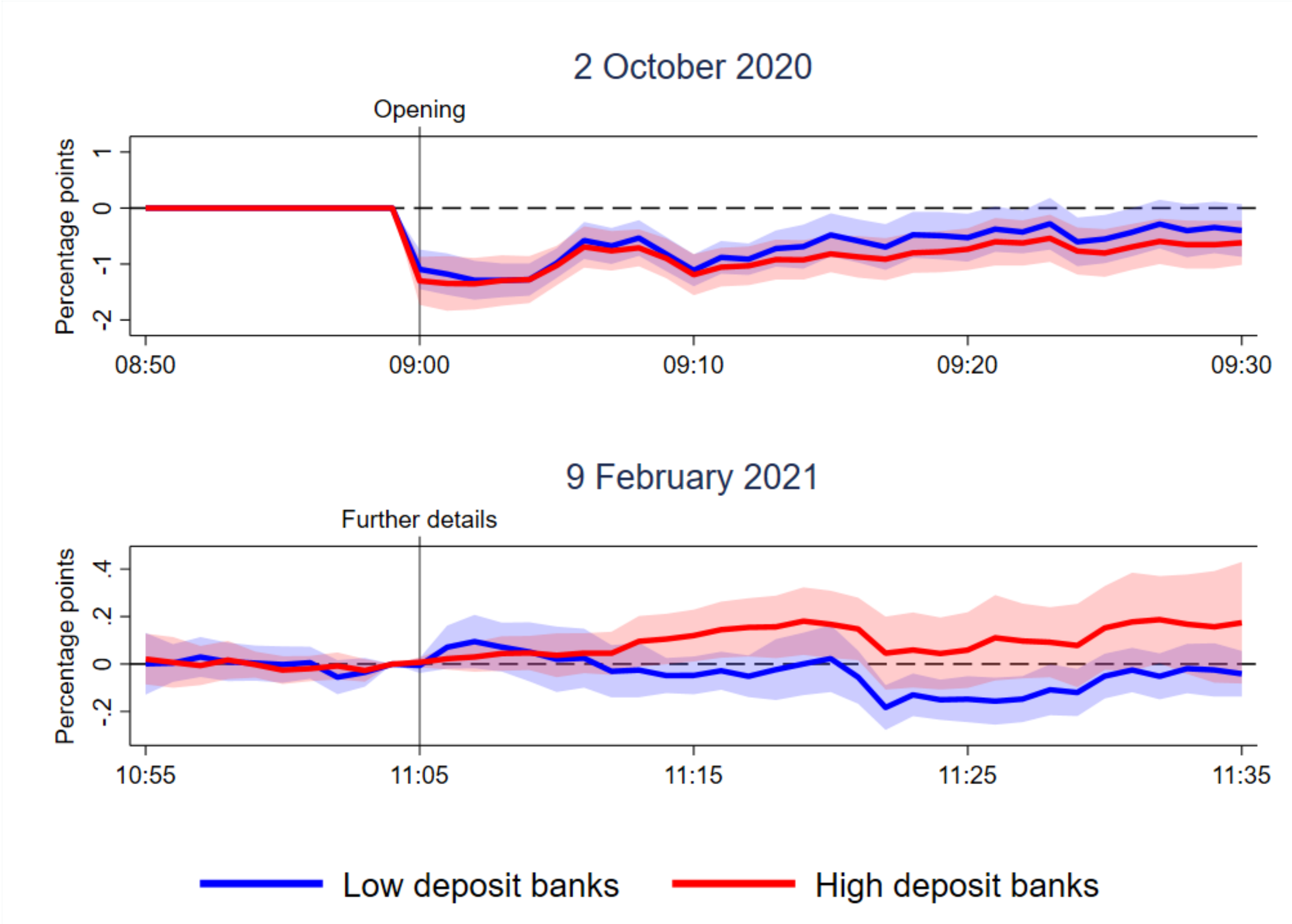
Notes: In the top panel, each dot represents a decile of the distribution of monthly bank stock returns in the euro area. The sample is an unbalanced panel of 323 euro area banks between June 2007 and September 2022. The vertical axis measures the average change in bank ROE one year after a change in a bank's stock price for each deciles of monthly bank stock returns in the euro area. The horizontal axis measures the average bank stock return within each decile. The line represents the linear prediction across the dots. In the bottom panel, the red dots report the estimation coefficients β^H of the regressions $\Delta\text{ROE}_{b,t,t+H} = \alpha_b^H + \alpha_{c,t}^H + \beta^H \text{Stock Return}_{b,t} + \gamma^H \Delta\text{ROE}_{b,t-1,t} + \Gamma^H X_{b,t} + \varepsilon_{b,t}^H$, for $H = \{1 \text{ year ahead}, \ldots, 5 \text{ years ahead}\}$. The sample is the same as the one used in the top panel. Each observation is a euro area bank b in a month t. $\Delta\text{ROE}_{b,t,t+H}$ is the change (in percentage points) in bank b's ROE between month t and month $t+H$. Stock $\text{Return}_{b,t}$ is the change (in percentages) of bank b's stock price between month $t-1$ and month t. $\text{ROE}_{b,t-1,t}$ is the change (in percentage points) in bank b's ROE between month $t-1$ and month t. $X_{b,t}$ are time-varying bank controls that include the log of bank assets, the deposit ratio, the securities and excess liquidity holdings as shares of assets, the CET1 ratio, the CDS spread, and the level of ROE. Bank and country-month fixed effects are represented by α_b^H and $\alpha_{c,t}^H$, respectively. The grey areas indicate the range of estimates spanned by plus or minus one standard deviation around the central estimate, the black dashes indicate the 95% confidence interval, with errors clustered at the bank level.

Figure A.3: Stock market returns of euro area banks by type of digital euro event and by reliance on deposit funding



Notes: The three columns of the two panels represent the three types of digital euro events detailed in Table A.1. In the top panel, we compute the average daily stock return of banks with a high (red circles) and low (blue dots) reliance on deposit funding across events belonging to each of the three categories. In the bottom panel, we do the same with the average abnormal daily returns estimated in Model (1).

Figure A.4: Minute-by-minute stock market returns of euro area banks around the key early digital euro events



Notes: The two panels report the minute-by-minute evolution of stock prices of euro area banks 10 minutes before and 30 minutes after two key digital euro events hit the markets. The events are the publication of the report on the digital euro on 2 October 2020 (top panel) and the publication of ECB Board member Panetta's interview on 9 February 2021 (bottom panel). For the event of 2 October 2020, the first Bloomberg News flash ("*ECB SAYS IT IS INTENSIFYING ITS WORK ON DIGITAL EURO") was at 8:00am (CET) and the second flash ("ECB Takes Major Step Toward Introducing a Digital Euro") was at 08:12am (CET). Stock prices were flat until market opening at 9:00am (CET). Hence, the event window goes from 08:50am to 09:30am. For the event of 9 February 2021, the Bloomberg News flash ("ECB's Panetta Floats 3,000-Euro Limit on Digital Cash: Spiegel") was at 11:04am (CET). Hence, the event window goes from 10:55am to 11:35am. The solid blue and red lines report the coefficients $\beta^E_{m,\text{Low}}$ and $\beta^E_{m,\text{High}}$ of the cross-sectional regressions $\Delta\text{Stock price}^E_{b,m} = \beta^E_{m,\text{Low}}\mathbb{1}_b(\text{Low deposit ratio}) + \beta^E_{m,\text{High}}\mathbb{1}_b(\text{High deposit ratio}) + \varepsilon^E_{b,m}$, for the two events $E = \{2\text{ October }2020, 9\text{ February }2021\}$, where the observation is a bank b. $\Delta\text{Stock price}^E_{b,m}$ is the percentage change in stock price between the minute before the key event and minute m, with m spanning 10 minutes before and 30 minutes after key event E (for the 2 October 2020, given that we start observing prices only after market opening, we consider as baseline level of stock prices the close-of-business level from the day before). $\mathbb{1}_b(\text{Low deposit ratio})$ and $\mathbb{1}_b(\text{High deposit ratio})$ are dummies indicating banks with low (below median) and high (above median) deposit ratios, respectively. The blue and red areas report the 95% confidence intervals computed with robust standard errors. The sample consists of 33 euro area banks with available intradaily stock market returns around the two events considered.

B Data and Sources

This appendix presents the full data set employed to calibrate the model in section 3.2.

Gross Domestic Product: Gross domestic product at market prices, Euro area 19 (fixed composition), Domestic (home or reference area), Total economy, Euro, Current prices, Non transformed data, Calendar and seasonally adjusted data. Source: ESA2010 National accounts, Main aggregates, Eurostat.

GDP Deflator: Gross domestic product at market prices, Euro area 19 (fixed composition), Domestic (home or reference area), Total economy, Index, Deflator (index), Non transformed data, Calendar and seasonally adjusted data. Source: ESA2010 National accounts, Main aggregates, Eurostat.

Private Consumption: Private final consumption, Individual consumption expenditure, Euro area 19 (fixed composition), World (all entities, including reference area, including IO), Households and non profit institutions serving households (NPISH), Euro, Current prices, Non transformed data, Calendar and seasonally adjusted data. Source: ESA2010 National accounts, Main aggregates, Eurostat.

Public Consumption: Government final consumption, Final consumption expenditure, Euro area 19 (fixed composition), World (all entities, including reference area, including IO), General government, Euro, Current prices, Non transformed data, Calendar and seasonally adjusted data. Source: ESA2010 National accounts, Main aggregates, Eurostat.

Gross fixed capital formation: Gross fixed capital formation, Euro area 19 (fixed composition), World (all entities, including reference area, including IO), Total economy, Fixed assets by type of asset (gross), Euro, Current prices, Non transformed data, Calendar and seasonally adjusted data.

Bank Deposits (Counterpart: MFIs): Deposit liabilities vis-a-vis euro area MFI reported by MFI excluding ESCB in the euro area (stock), Euro area (changing composition), Outstanding amounts at the end of the period (stocks), MFIs excluding ESCB reporting sector, Deposit liabilities, Total maturity, Euro, Euro area (changing composition) counterpart, Monetary financial institutions (MFIs) sector, denominated in Euro, data Neither seasonally nor working day adjusted. Source: MFI Balance Sheet Items (BSI Statistics), European Central Bank.

Bank Deposits (Counterpart: Non-MFIs): Deposit liabilities vis-a-vis euro area non-MFI reported by MFI excluding ESCB in the euro area (stock), Euro area (changing composition), Outstanding amounts at the end of the period (stocks), MFIs excluding ESCB reporting sector - Deposit liabilities, Total maturity, Euro - Euro area (changing composition) counterpart, Non-

MFIs sector, denominated in Euro, data Neither seasonally nor working day adjusted. Source: MFI Balance Sheet Items (BSI Statistics), European Central Bank.

Bank Capital and Reserves: Capital and reserves reported by MFI excluding ESCB in the euro area (stock), Euro area (changing composition), Outstanding amounts at the end of the period (stocks), MFIs excluding ESCB reporting sector - Capital and reserves, All currencies combined, World not allocated (geographically) counterpart, Unspecified counterpart sector sector, denominated in Euro, data Neither seasonally nor working day adjusted. Source: MFI Balance Sheet Items (BSI Statistics), European Central Bank.

Bank Loans to Households: Loans vis-a-vis euro area households reported by MFI excluding ESCB in the euro area (stock), Euro area (changing composition), Outstanding amounts at the end of the period (stocks), MFIs excluding ESCB reporting sector, Loans, Total maturity, All currencies combined, Euro area (changing composition) counterpart, Households and non-profit institutions serving households (S.14 and S.15) sector, denominated in Euro, data Neither seasonally nor working day adjusted. Source: MFI Balance Sheet Items (BSI Statistics), European Central Bank.

Bank Loans to NFCs: Loans vis-a-vis euro area NFC reported by MFI excluding ESCB in the euro area (stock), Euro area (changing composition), Outstanding amounts at the end of the period (stocks), MFIs excluding ESCB reporting sector - Loans, Total maturity, All currencies combined - Euro area (changing composition) counterpart, Non-Financial corporations (S.11) sector, denominated in Euro, data Neither seasonally nor working day adjusted. Source: MFI Balance Sheet Items (BSI Statistics), European Central Bank.

Bank Holdings of Government Debt: Holdings of debt securities issued by euro area General Government reported by MFI excluding ESCB in the euro area (stock), Euro area (changing composition), Outstanding amounts at the end of the period (stocks), MFIs excluding ESCB reporting sector, Debt securities held, Total maturity, All currencies combined, Euro area (changing composition) counterpart, General Government sector, denominated in Euro, data Neither seasonally nor working day adjusted. Source: MFI Balance Sheet Items (BSI Statistics), European Central Bank.

Reserves: Liabilities to euro area credit institutions related to MPOs denominated in euro - Eurosystem, Euro area (changing composition), Eurosystem reporting sector, Liabilities to euro area credit institutions related to MPOs denominated in euro, Euro, Euro area (changing composition) counterpart. Source: Internal Liquidity Management (ILM Statistics), European Central Bank.

Banknotes (Cash): Banknotes in circulation - Eurosystem, Euro area (changing composition), Eurosystem reporting sector, Banknotes in circulation, Euro, World not allocated (geographically) counterpart. Source: MFI Balance Sheet Items (BSI Statistics), European Central Bank.

Deposit Interest Rate: Bank interest rates, overnight deposits from households - euro area, Euro area (changing composition), Annualised agreed rate (AAR) / Narrowly defined effective rate (NDER), Credit and other institutions (MFI except MMFs and central banks) reporting sector, Overnight deposits, Total original maturity, New business coverage, Households and non-profit institutions serving households (S.14 and S.15) sector, denominated in Euro. Source: MFI Interest Rate Statistics (MIR Statistics), European Central Bank.

NFC Loans Interest Rate: Bank interest rates, loans to corporations with an original maturity of up to one year (outstanding amounts) - euro area, Euro area (changing composition), Annualised agreed rate (AAR) / Narrowly defined effective rate (NDER), Credit and other institutions (MFI except MMFs and central banks) reporting sector, Loans, Up to 1 year original maturity, Outstanding amount business coverage, Non-Financial corporations (S.11) sector, denominated in Euro. Source: MFI Interest Rate Statistics (MIR Statistics), European Central Bank.

Deposit Facility Rate: ECB Deposit facility, date of changes (raw data), Level. Euro area (changing composition), Key interest rate, ECB Deposit facility, date of changes (raw data), Level, Euro, provided by ECB. Source: Financial market data (MF Statistics), European Central Bank.

Lending Facility Rate: ECB Marginal lending facility - date of changes (raw data) - Level. Euro area (changing composition), Key interest rate, ECB Marginal lending facility, date of changes (raw data), Level, Euro, provided by ECB. Source: Financial market data (MF Statistics), European Central Bank.

C Equations of the Model

This section presents the full set of equilibrium equations of the DSGE model under the baseline scenario.

C.1 Patient Households

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

$$\begin{aligned} c_{p,t} + q_t(h_{p,t} - h_{p,t-1}) + m_t + f(m_t) + cbdc_t + d_t + b_{p,t} + \omega_T T_t \\ = \frac{m_{t-1}}{\pi_t} + R_{cbdc,t-1}\frac{cbdc_{t-1}}{\pi_t} + R_{d,t-1}\frac{d_{t-1}}{\pi_t} + R_{g,t-1}\frac{b_{p,t-1}}{\pi_t} + w_t n_{p,t} + \Omega_t, \end{aligned} \quad \text{(C.1)}$$

Their choice variables are $c_{p,t}$, $h_{p,t}$, d_t, m_t, $cbdc_t$, $b_{p,t}$ and $n_{p,t}$. The optimality conditions of the problem read

$$\lambda_t^p = \left[c_{p,t} - \frac{n_{p,t}^{1+\phi}}{(1+\phi)}\right]^{-\sigma_h}, \quad \text{(C.2)}$$

$$q_t \lambda_t^p = \frac{j_{p,t}}{h_{p,t}} + \beta_p E_t\left(q_{t+1}\lambda_{t+1}^p\right), \quad \text{(C.3)}$$

$$\lambda_t^p = \beta_p E_t\left(\lambda_{t+1}^p R_{d,t}/\pi_{t+1}\right) + \frac{\chi_{z,t}}{z_t}\omega_d\left(\frac{z_t}{d_t}\right)^{1/\eta_{z,t}}, \quad \text{(C.4)}$$

$$\lambda_t^p = \beta_p E_t\left(\lambda_{t+1}^p R_{cbdc,t}/\pi_{t+1}\right) + \frac{\chi_{z,t}}{z_t}\left(\frac{z_t}{cbdc_t}\right)^{1/\eta_{z,t}}, \quad \text{(C.5)}$$

$$\lambda_t^p(1+f_m) = \beta_p E_t\left(\lambda_{t+1}^p/\pi_{t+1}\right) + \frac{\chi_{z,t}}{z_t}\left(\frac{z_t}{m_t}\right)^{1/\eta_{z,t}}, \quad \text{(C.6)}$$

$$\lambda_t^p = \beta_p E_t\left(\lambda_{t+1}^p R_{g,t}/\pi_{t+1}\right), \quad \text{(C.7)}$$

$$w_t = n_{p,t}^{\phi}, \quad \text{(C.8)}$$

where λ_t^p is the Lagrange multiplier on the budget constraint of the representative patient household.

C.2 Impatient Households

The representative impatient household chooses the trajectories of consumption $c_{i,t}$, property housing $h_{i,t}$, hours worked $n_{i,t}$, and demand for loans $l_{i,t}$ that maximizes its objective function subject to a budget constraint and a borrowing limit:

$$c_{i,t} + q_t \left(h_{i,t} - h_{i,t-1} \right) + R_{i,t-1} \frac{l_{i,t-1}}{\pi_t} + \left(1 - \omega_T \right) T_t = l_{i,t} + w_t n_{i,t}, \tag{C.9}$$

$$l_{i,t} \leq m_{H,t} E_t \left(\frac{q_{t+1}}{R_{i,t}} h_{i,t} \pi_{t+1} \right). \tag{C.10}$$

The resulting optimality conditions are

$$\lambda_t^i = \left[c_{i,t} - \frac{n_{i,t}^{1+\phi}}{(1+\phi)} \right]^{-\sigma_h}, \tag{C.11}$$

$$\lambda_t^i \left[q_t - E_t \left(m_{H,t} \frac{q_{t+1}}{R_{i,t}} \pi_{t+1} \right) \right] = \frac{j_{i,t}}{h_{i,t}} + \beta_i E_t \left[q_{t+1} \lambda_{t+1}^i \left(1 - m_{H,t} \right) \right], \tag{C.12}$$

$$w_t = n_{i,t}^{\phi}. \tag{C.13}$$

where λ_t^i is the Lagrange multiplier on the budget constraint of the representative impatient household.

C.3 Banks

Banks maximize their objective function subject to a balance sheet identity, a cash flow restriction, a capital adequacy constraint, a liquidity (reserves) requirement and a central banks' collateral requirement

$$L_{i,t} + L_{e,t} + b_{b,t} + \widetilde{R}_{b,t} = e_t + D_t + f_t, \tag{C.14}$$

$$\begin{aligned} &\Omega_{b,t} + e_t - (1-\delta^e) \frac{e_{t-1}}{\pi_t} \\ &= \frac{\left(r_{i,t-1} L_{i,t-1} + r_{e,t} L_{e,t-1} + r_{g,t-1} b_{b,t-1} + r_{\widetilde{R},t-1} \widetilde{R}_{b,t-1} - r_{d,t-1} D_{t-1} - r_{f,t-1} f_{t-1} \right)}{\pi_t}, \end{aligned} \tag{C.15}$$

$$D_t + f_t \leq \gamma_i L_{i,t} + \gamma_e L_{e,t} + \gamma_b b_{b,t} + \gamma_{\widetilde{R}} \widetilde{R}_{b,t}, \tag{C.16}$$

$$\theta_{R,t} D_t \leq \widetilde{R}_{b,t}, \tag{C.17}$$

$$f_t \leq \theta_{b,t} E_t \left(\frac{b_{b,t}}{R_{f,t}} \pi_{t+1} \right). \tag{C.18}$$

The law of motion for bank equity reads

$$e_t = J_{b,t} - \Omega_{b,t} + (1-\delta^e) e_{t-1}/\pi_t. \tag{C.19}$$

Their choice variables are $\Omega_{b,t}$, $L_{i,t}$, $L_{e,t}$, $b_{b,t}$, $\widetilde{R}_{b,t}$, D_t and f_t.The resulting optimality conditions read

$$\frac{1}{\Omega_{b,t}^{\frac{1}{\sigma}}}+\mu_{e,t}\gamma_e=E_t\left[\Lambda_{t,t+1}\frac{\left(r_{e,t+1}+1-\delta^e\right)/\pi_{t+1}}{\Omega_{b,t+1}^{\frac{1}{\sigma}}}\right], \tag{C.20}$$

$$\frac{1}{\Omega_{b,t}^{\frac{1}{\sigma}}}+\mu_{e,t}\gamma_i=E_t\left[\Lambda_{t,t+1}\frac{\left(r_{i,t}+1-\delta^e\right)/\pi_{t+1}}{\Omega_{b,t+1}^{\frac{1}{\sigma}}}\right], \tag{C.21}$$

$$\frac{1}{\Omega_{b,t}^{\frac{1}{\sigma}}}+\mu_{\widetilde{R},t}+\mu_{e,t}=E_t\left[\Lambda_{t,t+1}\frac{\left(r_{\widetilde{R},t}+1-\delta^e\right)/\pi_{t+1}}{\Omega_{b,t+1}^{\frac{1}{\sigma}}}\right], \tag{C.22}$$

$$\frac{1}{\Omega_{b,t}^{\frac{1}{\sigma}}}+\mu_{f,t}\theta_{f,t}E_t\left(\frac{\pi_{t+1}}{R_{f,t}}\right)+\mu_e=E_t\left[\Lambda_{t,t+1}\frac{\left(r_{g,t}+1-\delta^e\right)/\pi_{t+1}}{\Omega_{b,t+1}^{\frac{1}{\sigma}}}\right], \tag{C.23}$$

$$\frac{1}{\Omega_{b,t}^{\frac{1}{\sigma}}}+\mu_{e,t}+\mu_{\widetilde{R},t}\theta_{R,t}=E_t\left[\Lambda_{t,t+1}\frac{\left(r_{d,t}+1-\delta^e\right)/\pi_{t+1}}{\Omega_{b,t+1}^{\frac{1}{\sigma}}}\right], \tag{C.24}$$

$$\frac{1}{\Omega_{b,t}^{\frac{1}{\sigma}}}+\mu_{e,t}+\mu_{f,t}=E_t\left[\Lambda_{t,t+1}\frac{\left(r_{f,t}+1-\delta^e\right)/\pi_{t+1}}{\Omega_{b,t+1}^{\frac{1}{\sigma}}}\right]. \tag{C.25}$$

where $\mu_{e,t}$, $\mu_{\widetilde{R},t}$, and $\mu_{f,t}$ are the multipliers on the capital adequacy constraint, the reserve requirement, and the central bank's collateral constraint, respectively.

C.4 Entrepreneurial Managers

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

$$\Omega_{e,t}+R_{e,t}\frac{l_{e,t-1}}{\pi_t}+q_{k,t}\left[k_{e,t}-(1-\delta_t^k)k_{e,t-1}\right]+q_t(h_{e,t}-h_{e,t-1})=r_{h,t}h_{e,t-1}+r_{k,t}u_tk_{e,t-1}+l_{e,t}+J_{er,t}, \tag{C.26}$$

$$l_{e,t}\leq m_{K,t}E_t\left[\frac{q_{k,t+1}}{R_{e,t+1}}(1-\delta_{t+1}^k)k_{e,t}\pi_{t+1}\right], \tag{C.27}$$

where

$$\delta_t^k\left(u_t\right)=\delta_0^k+\delta_1^k(u_t-1)+\frac{\delta_2^k}{2}\left(u_t-1\right)^2. \tag{C.28}$$

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

$$\Omega_{e,t}^{-\frac{1}{\sigma}}q_t=\Lambda_{t,t+1}E_t\left[\Omega_{e,t+1}{}^{-\frac{1}{\sigma}}\left(q_{t+1}+r_{h,t+1}\right)\right], \tag{C.29}$$

$$\Omega_{e,t}^{-\frac{1}{\sigma}} \left\{ q_{k,t} - m_{K,.t} E_t \left[\frac{q_{k,t+1}}{R_{e,t+1}} (1-\delta_{t+1}^k) \pi_{t+1} \right] \right\}$$
$$= \Lambda_{t,t+1} E_t \left\{ \Omega_{e,t+1}{}^{-\frac{1}{\sigma}} \left[q_{k,t+1}(1-\delta_t^k)(1-m_{K,t}) + u_{t+1} r_{k,t+1} \right] \right\}, \quad \text{(C.30)}$$

$$\delta_1^k + \delta_2^k (u_t - 1) = r_{k,t}. \quad \text{(C.31)}$$

C.5 Entrepreneurial Retailers

There is a continuum of entrepreneurial retailers (also referred to as intermediate non-housing good producers). Each intermediate good producer j operates the following Cobb-Douglas production function:

$$Y_t(j) = A_t \left[u_t(j) k_{e,t-1}(j) \right]^{\alpha} h_{e,t-1}(j)^{\nu} N_t(j)^{(1-\alpha-\nu)}, \quad \text{(C.32)}$$

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

$$\frac{w_t}{r_{k,t}} = \frac{(1-\alpha-\nu)}{\alpha} \frac{u_t k_{e,t-1}}{N_t}, \quad \text{(C.33)}$$

$$\frac{r_{h,t}}{r_{k,t}} = \frac{\nu}{\alpha} \frac{u_t k_{e,t-1}}{h_{e,t-1}}, \quad \text{(C.34)}$$

$$mc_t = \frac{(w_t)^{(1-\alpha-\nu)} (r_{k,t})^{\alpha} (r_{h,t})^{\nu}}{A_t (1-\alpha-\nu)^{(1-\alpha-\nu)} \alpha^{\alpha} \nu^{\nu}}. \quad \text{(C.35)}$$

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

$$g_t^1 = \lambda_t^p mc_t Y_t + \beta_p \theta E_t \left(\frac{\pi_t^{\chi_\pi}}{\pi_{t+1}} \right)^{-\varepsilon} g_{t+1}^1, \quad \text{(C.36)}$$

$$g_t^2 = \lambda_t^p \pi_t^* Y_t + \beta_p \theta E_t \left(\frac{\pi_t^{\chi_\pi}}{\pi_{t+1}} \right)^{1-\varepsilon} \left(\frac{\pi_t^*}{\pi_{t+1}^*} \right) g_{t+1}^2, \quad \text{(C.37)}$$

$$\varepsilon g_t^1 = (\varepsilon - 1) g_t^2. \quad \text{(C.38)}$$

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

$$1 = \theta \left(\frac{\pi_{t-1}^{\chi_\pi}}{\pi_t} \right)^{1-\varepsilon} + (1-\theta) \pi_t^{*1-\varepsilon}, \quad \text{(C.39)}$$

and

$$\upsilon_t = \theta \left(\frac{\pi_{t-1}^{\chi_\pi}}{\pi_t} \right)^{-\varepsilon} \upsilon_{t-1} + (1-\theta) \pi_t^{*-\varepsilon}. \quad \text{(C.40)}$$

Profits from each intermediate good producer j are transferred to entrepreneurial managers:

$$J_{er,t}(j) = Y_t(j) - [r_{k,t}k_{e,t-1}(j) + r_{h,t}h_{e,t-1}(j) + w_t N_t(j)] . \tag{C.41}$$

C.6 Capital and Final Goods Producers

The representative final goods producer maximizes $P_t Y_t - \int_0^1 P_t(j) Y_t(j) dj$ with respect to the demand for the intermediate good, $Y_t(j)$. 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: $Y_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\varepsilon} Y_t$, $\forall j$.

Capital-good-producing firms seek to maximize their objective function with respect to net investment in physical capital, I_t. The resulting optimal condition is

$$1 = q_{k,t}\left[1 - \frac{\psi_I}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2 - \psi_I\left(\frac{I_t}{I_{t-1}} - 1\right)\frac{I_t}{I_{t-1}}\right] + E_t\left[\Lambda_{t,t+1}q_{k,t+1}\psi_I\left(\frac{I_{t+1}}{I_t} - 1\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right]. \tag{C.42}$$

The law of motion for physical capital reads

$$K_t = (1 - \delta_t^k)K_{t-1} + I_t\left[1 - \frac{\psi_I}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right]. \tag{C.43}$$

C.7 Government

Tax revenues are collected from households in a lump-sum fashion and determined according to a fiscal rule

$$T_t = \phi_p b_{p,t-1} + \phi_b b_{b,t-1}. \tag{C.44}$$

Government spending is assumed to be equal to a constant fraction of steady state real output

$$G_t = \varrho Y^{ss}. \tag{C.45}$$

Supply of short-term government bonds is endogenously determined by the following intertemporal budget constraint

$$R_{g,t-1}\frac{B_{g,t-1}}{\pi_t} + G_t = T_t + B_{g,t} + \Omega_{cb,t}. \tag{C.46}$$

C.8 Central Bank

The central bank sets the lending facility rate $r_{f,t}$ according to a Taylor-type policy rule:

$$r_{f,t} = \rho_r r_{f,t-1} + (1-\rho_r)\left(r_f^{ss} + \alpha_\pi \tilde{\pi}_t + \alpha_Y \tilde{y}_t\right) + e_{rf,t}. \tag{C.47}$$

A constant corridor of width $\alpha > 0$ is assumed to be maintained between the lending facility rate and the deposit facility rate,

$$r_{\widetilde{R},t} = r_{f,t} - \alpha. \tag{C.48}$$

According to the balance sheet of the central bank:

$$F_t = \widetilde{R}_t + M_t + CBDC_t. \tag{C.49}$$

Central bank's profits evolve as

$$\Omega_{cb,t} = \widetilde{R}_t + M_t + CBDC_t + R_{f,t-1}\frac{F_{t-1}}{\pi_t} - R_{\widetilde{R},t-1}\frac{\widetilde{R}_{t-1}}{\pi_t} - \frac{M_{t-1}}{\pi_t} - R_{cbdc,t-1}\frac{cbdc_{t-1}}{\pi_t} - F_t. \tag{C.50}$$

In the baseline scenario, CBDC supply is set according to the following policy rule:

$$CBDC_t = \phi_Y Y^{ss}. \tag{C.51}$$

C.9 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:

$$Y_t = C_t + q_{k,t} I_t + G_t + \delta^e e_{t-1} + f(m_t). \tag{C.52}$$

Similarly, in equilibrium labor demand equals total labor supply,

$$N_t = n_{p,t} + n_{i,t}. \tag{C.53}$$

The stock of physical capital produced by capital goods producers must equal the demand for this good coming from households

$$K_t = k_{e,t}. \tag{C.54}$$

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

$$\overline{H} = h_{p,t} + h_{i,t} + h_{e,t}. \tag{C.55}$$

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

$$l_{i,t} + l_{e,t} = L_t. \tag{C.56}$$

In equilibrium, the supply of government bonds equals the demand for this asset coming from patient households and banks

$$b_{p,t} + b_{b,t} = B_{g,t}. \tag{C.57}$$

Bank's reserves are a liability of the central bank

$$\widetilde{R}_{b,t} = \widetilde{R}_t. \tag{C.58}$$

CBDC issued by the central bank equals demand for that means of payment

$$CBDC_t = cbdc_t. \tag{C.59}$$

Cash issued by the central bank equals demand for that monetary instrument

$$M_t = m_t. \tag{C.60}$$

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

$$d_t = D_t. \tag{C.61}$$

In equilibrium, banks' demand for central bank funding equals central bank's supply of funding to banks

$$f_t = F_t. \tag{C.62}$$

C.10 Shocks

The following zero-mean, AR(1) shocks are present in the baseline calibration model: $\varepsilon_{h,t}$, $\varepsilon_{z,t}$, $\varepsilon_{\eta,t}$, $\varepsilon_{mh,t}$, $\varepsilon_{mk,t}$, A_t, $\varepsilon_{\theta_R,t}$, $_{\theta_b,t}$. These shocks follow the processes given by:

$$\log \varepsilon_{h,t} = \rho_h \log \varepsilon_{h,t-1} + e_{h,t},\ \ e_{h,t} \sim N(0, \sigma_h), \tag{C.63}$$

$$\log \varepsilon_{z,t} = \rho_z \log \varepsilon_{z,t-1} + e_{z,t},\ \ e_{z,t} \sim N(0, \sigma_z), \tag{C.64}$$

$$\log \varepsilon_{\eta,t} = \rho_z \log \varepsilon_{\eta,t-1} + e_{\eta,t},\ \ e_{\eta,t} \sim N(0, \sigma_\eta), \tag{C.65}$$

$$\log \varepsilon_{mh,t} = \rho_{mh} \log \varepsilon_{mh,t-1} + e_{mh,t},\ \ e_{mh,t} \sim N(0, \sigma_{mh}), \tag{C.66}$$

$$\log \varepsilon_{mk,t} = \rho_{mk} \log \varepsilon_{mk,t-1} + e_{mk,t},\ \ e_{mk,t} \sim N(0, \sigma_{mk}), \tag{C.67}$$

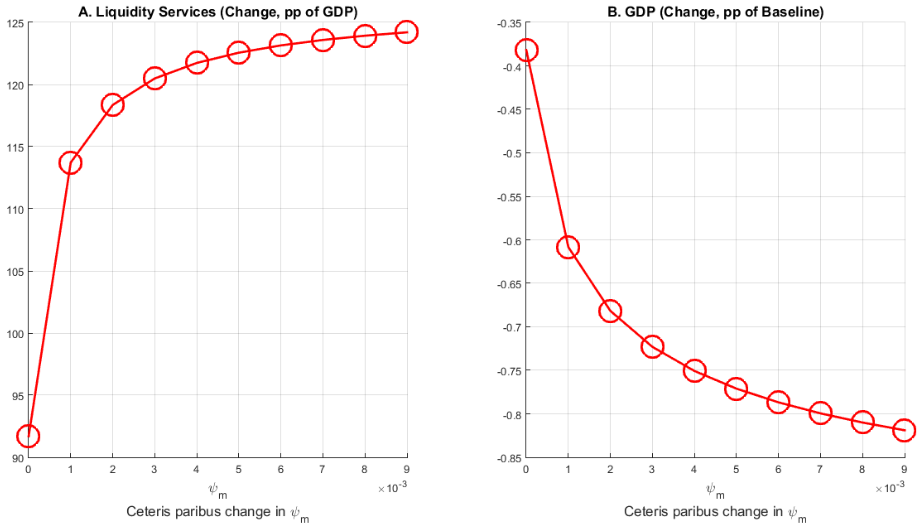
$$\log A_t = \rho_A \log A_{t-1} + e_{A,t},\ \ e_{A,t} \sim N(0, \sigma_A). \tag{C.68}$$

$$\log \varepsilon_{\theta_R,t} = \rho_{\theta_R} \log \varepsilon_{\theta_R,t-1} + e_{\theta_R,t},\ \ e_{\theta_R,t} \sim N(0, \sigma_{\theta_R}). \tag{C.69}$$

$$\log \varepsilon_{\theta_b,t} = \rho_{\theta_b} \log \varepsilon_{\theta_b,t-1} + e_{\theta_b,t},\ \ e_{\theta_b,t} \sim N(0, \sigma_{\theta_b}). \tag{C.70}$$

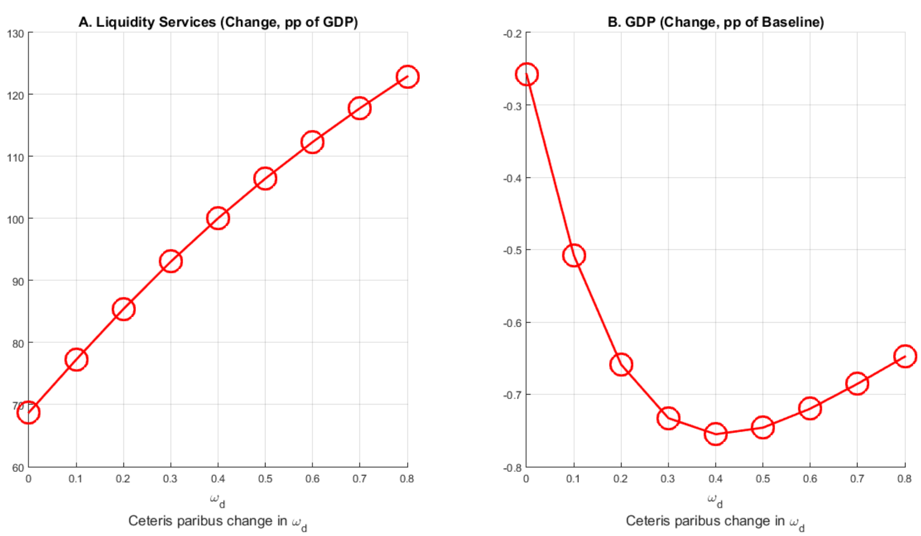
D Additional Quantitative Assessment

Figure D.1: Liquidity services expansion: ψ_m



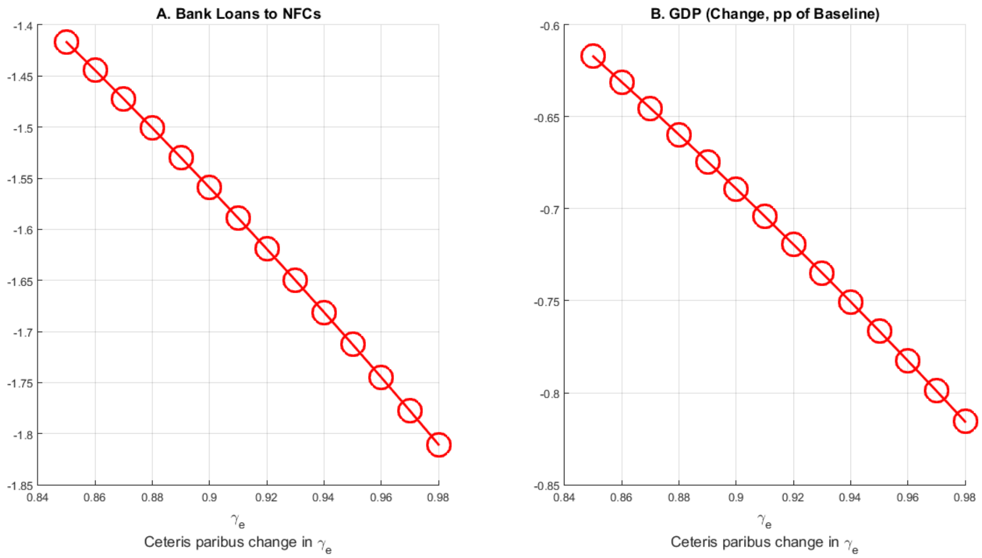
Notes: CBDC-induced changes in the steady state level of liquidity services (expressed in percentage points of GDP) and GDP (expressed in percentage points of its baseline level) - associated with the scenario under which CBDC supply in equilibrium is equal to 64.4% of quarterly GDP (i.e., zero CBDC interest rate) - for different values of the cash storage cost parameter, ψ_m.

Figure D.2: Liquidity services expansion: ω_d



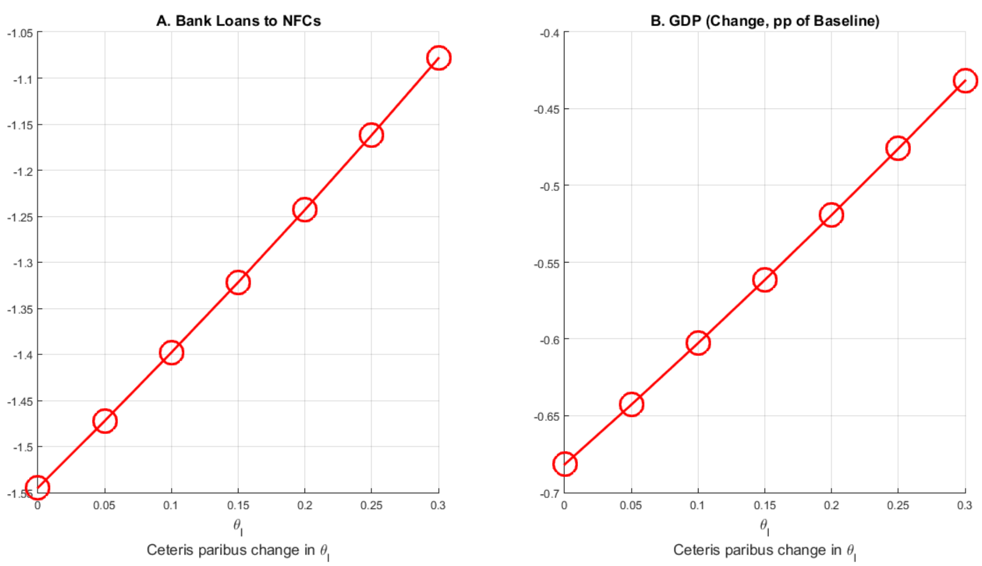
Notes: CBDC-induced changes in the steady state level of liquidity services (expressed in percentage points of GDP) and GDP (expressed in percentage points of its baseline level) -associated with the scenario under which CBDC supply in equilibrium is equal to 64.4% of quarterly GDP (i.e., zero CBDC interest rate) - for different values of the weight parameter of bank deposits in liquidity services, ω_d.

Figure D.3: Bank disintermediation: γ_e



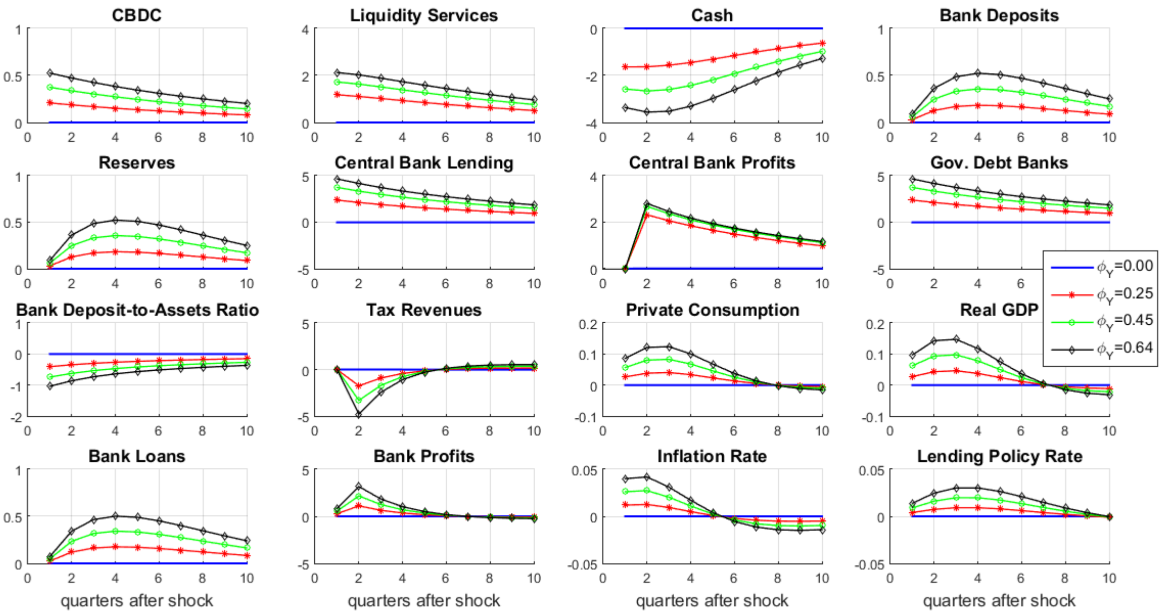
Notes: CBDC-induced changes in the steady state level of bank loans to non-financial corporations (expressed in percentage points of GDP) and GDP (expressed in percentage points of its baseline level) associated with the scenario under which CBDC supply in equilibrium is equal to 64.4% of quarterly GDP (i.e., zero CBDC interest rate) - for different values of sectoral (NFCs) capital requirements parameter γ_e.

Figure D.4: Bank disintermediation: θ_l



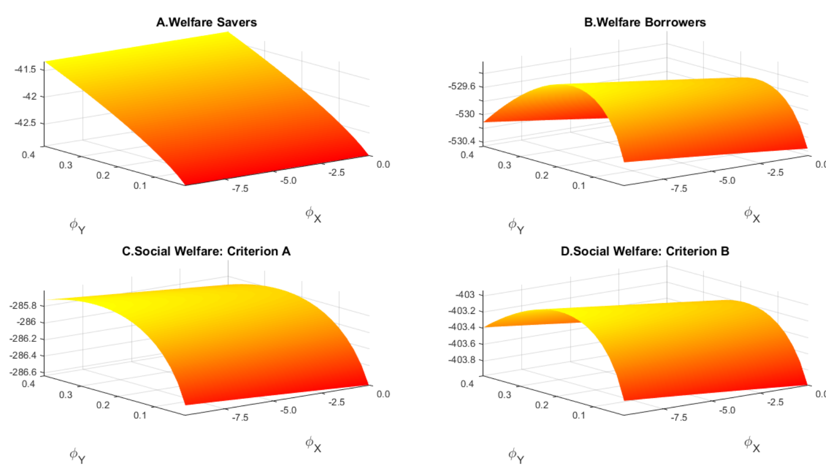
Notes: CBDC-induced changes in the steady state level of bank loans to non-financial corporations (expressed in percentage points of GDP) and GDP (expressed in percentage points of its baseline level) associated with the scenario under which CBDC supply in equilibrium is equal to 64.4% of quarterly GDP (i.e., zero CBDC interest rate) - for different values of the collateral requirement on NFC loans parameter, θ_l.

Figure D.5: Transmission and cyclical effects. Impulse-responses to a positive CBDC supply shock



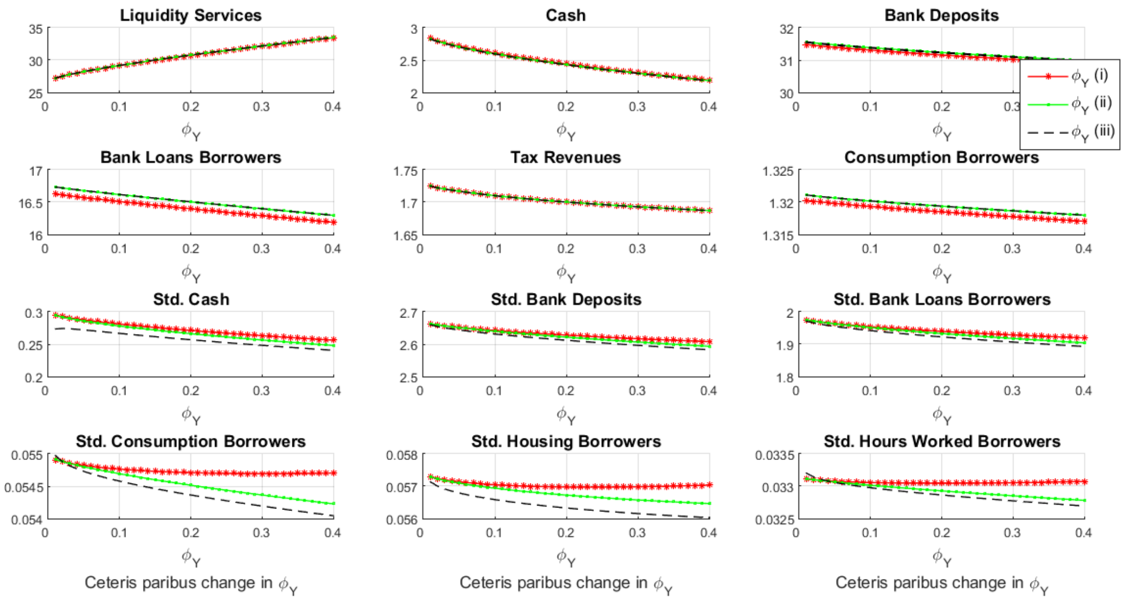
Notes: Variables are expressed in percentage deviations from the steady state with the exceptions of CBDC, the inflation rate and the lending policy rate, which are shown as absolute deviations from the steady state. These two rates have been annualized and are expressed in percentage points. The solid line refers to the baseline (no CBDC) scenario. The starred, dotted, and diamond lines make reference to alternative scenarios under which CBDC supply in equilibrium is equal to 25%, 45% and 64% of quarterly real GDP, respectively.

Figure D.6: Welfare effects of CBDC quantity rule (iii) (welfare effects of ceteris paribus changes in $\phi_Y - \phi_X$)



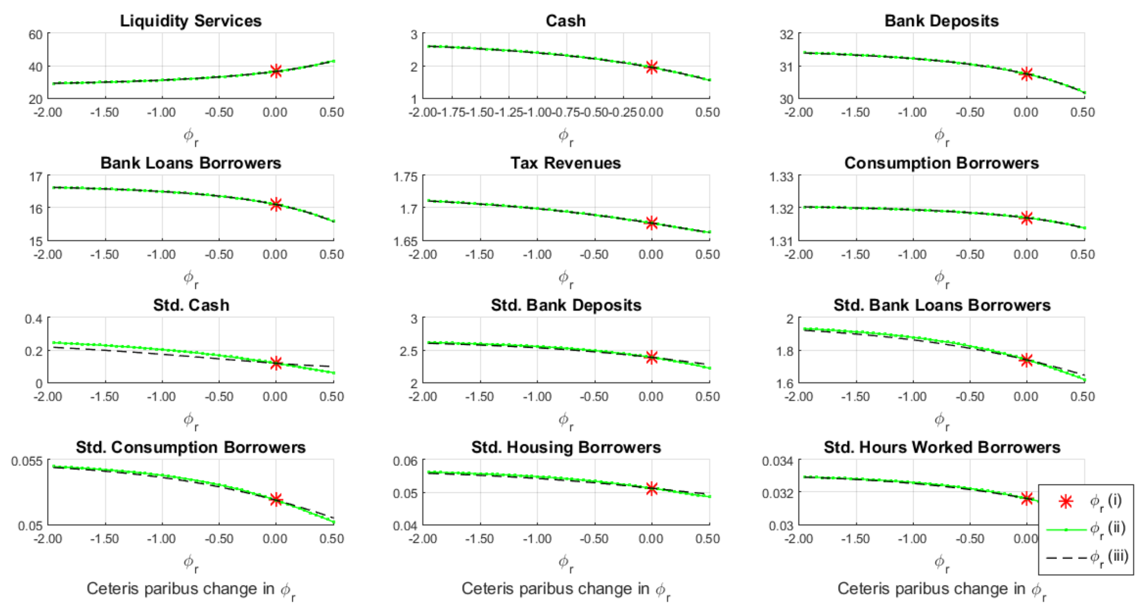
Notes: Second-order approximation to the unconditional welfare of savers and borrowers as well as to the unconditional social welfare under welfare criteria "A" and "B" as a function of CBDC policy parameters ϕ_Y and ϕ_X under CBDC quantity rule (iii).

Figure D.7: Mean and volatility effects of CBDC quantity rules (welfare effects of ceteris paribus changes in ϕ_Y)



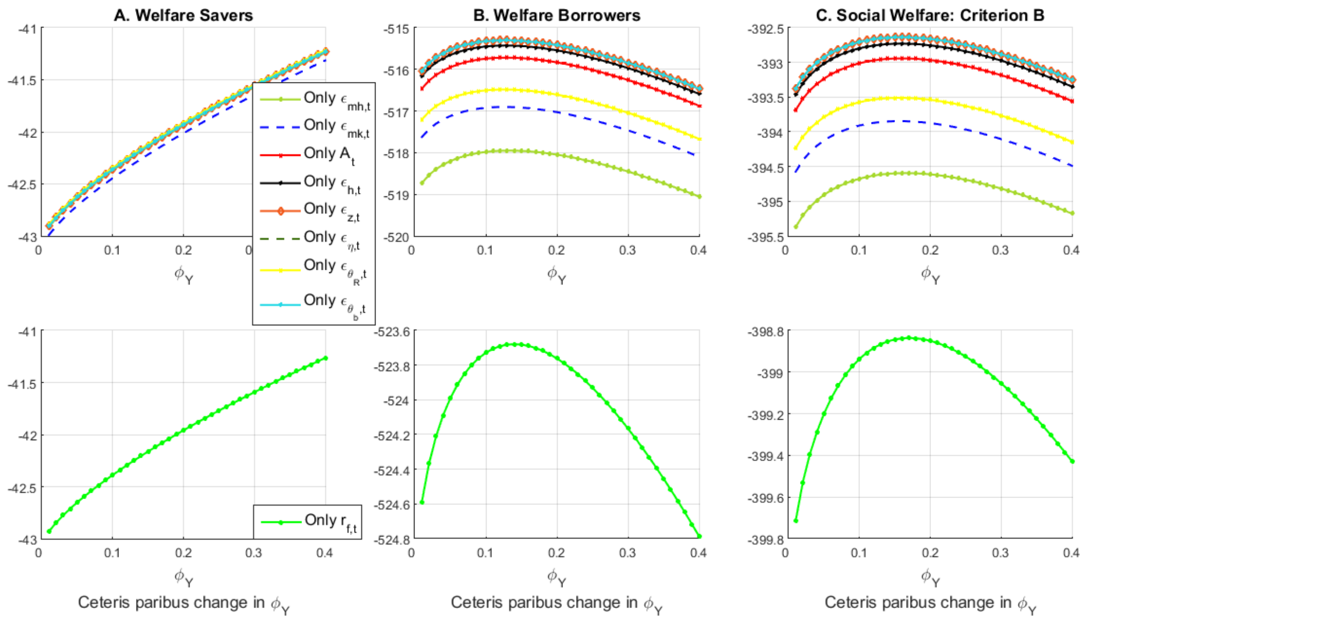
Notes: Second-order approximation to the stochastic mean and standard deviation of key selected aggregates as a function of CBDC policy parameter ϕ_Y. The starred line, the dotted line, and the dashed line relate to CBDC quantity rules (i), (ii) and (iii), respectively.

Figure D.8: Mean and volatility effects of CBDC interest rate rules (welfare effects of ceteris paribus changes in ϕ_r)



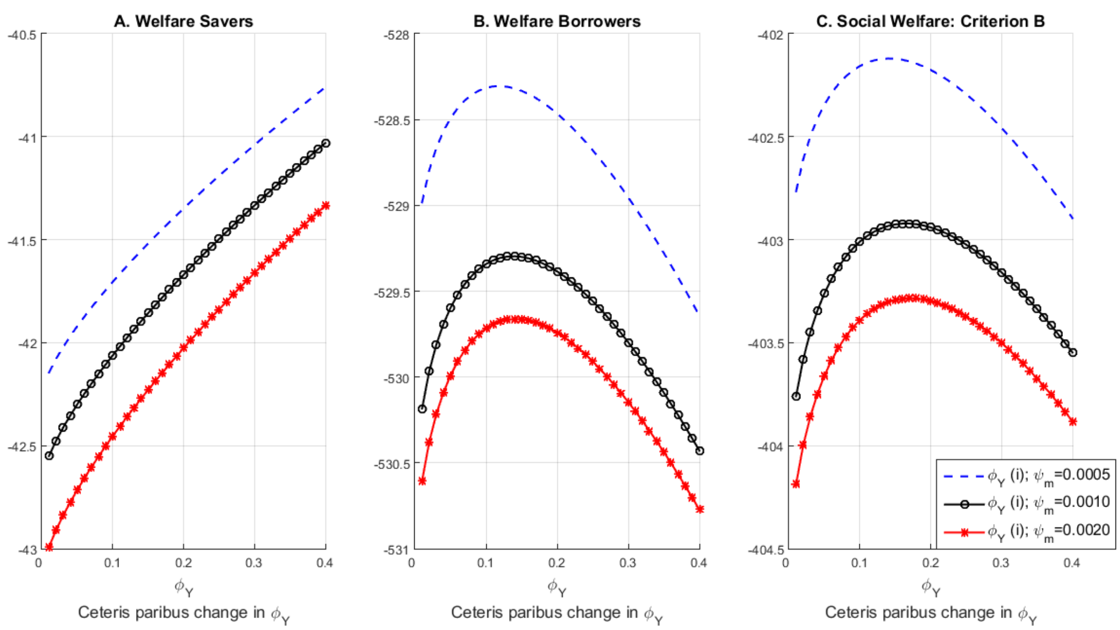
Notes: Second-order approximation to the stochastic mean and standard deviation of key selected aggregates as a function of CBDC policy parameter ϕ_r. The star, the dotted line, and the dashed line relate to CBDC interest rate rules (i), (ii) and (iii), respectively.

Figure D.9: Welfare effects of CBDC quantity rules by types of shocks (shutting down shocks)



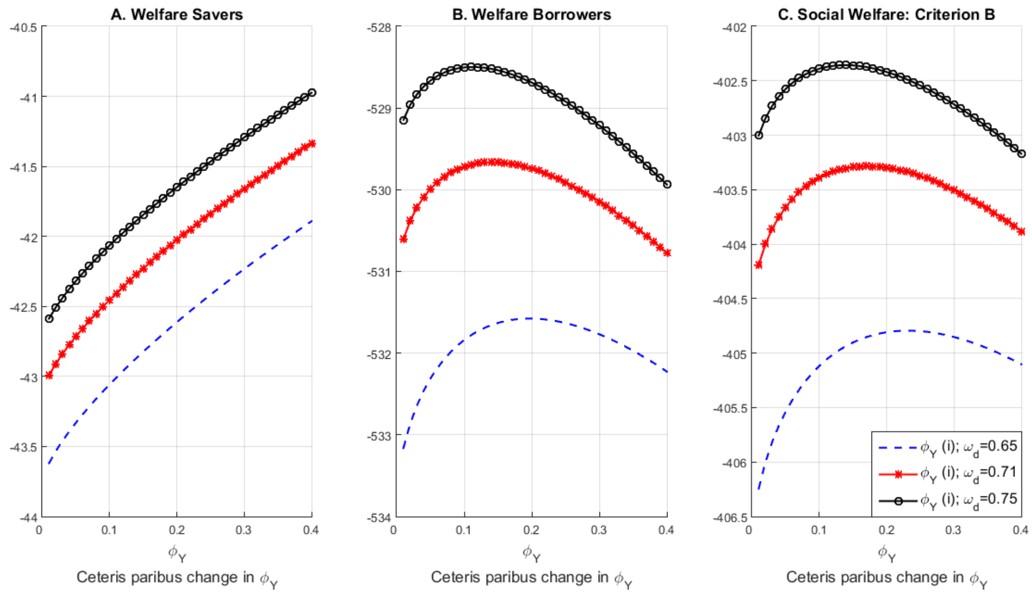
Notes: Second-order approximation to the unconditional welfare of savers and borrowers as well as to the unconditional social welfare under welfare criterion "B" as a function of CBDC policy parameter ϕ_Y under quantity rule of type (i). Each of the 9 lines informs about the welfare effects of ceteris paribus changes in ϕ_Y when only one of the nine types of shocks that are considered under the baseline calibration hits this model economy.

Figure D.10: Robustness Checks: ψ_m (welfare effects of ceteris paribus changes in ϕ_Y)



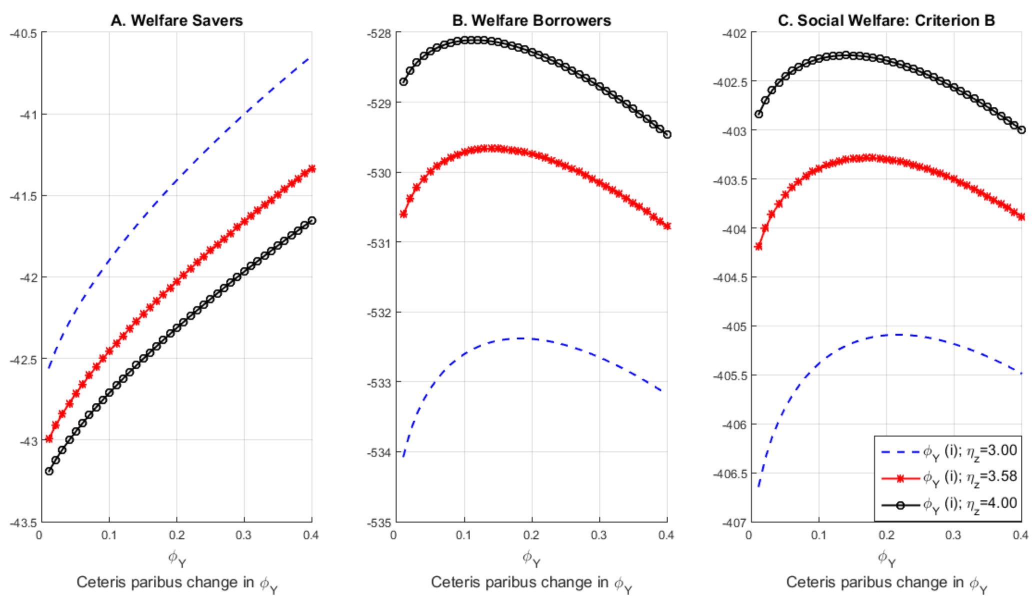
Notes: Second-order approximation to the unconditional welfare of savers and borrowers as well as to the unconditional social welfare under welfare criterion "B" for CBDC quantity rule (i) as a function of policy parameter ϕ_Y, for alternative values of the cash storage cost parameter, ψ_m. The starred line refers to the baseline calibration whereas the dotted and dashed lines relate to alternative parameterization scenarios.

Figure D.11: Robustness Checks: ω_d (welfare effects of ceteris paribus changes in ϕ_Y)



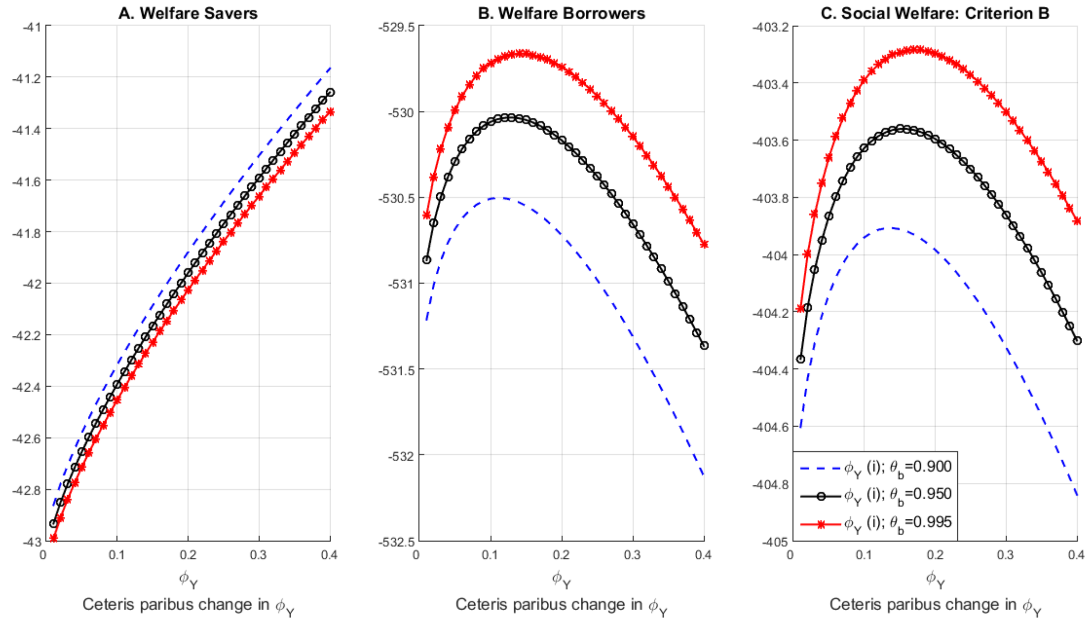
Notes: Second-order approximation to the unconditional welfare of savers and borrowers as well as to the unconditional social welfare under welfare criterion "B" for CBDC quantity rule (i) as a function of policy parameter ϕ_Y, for alternative values of the deposits preference parameter ω_d. The starred line refers to the baseline calibration whereas the dotted and dashed lines relate to alternative parameterization scenarios.

Figure D.12: Robustness Checks: η_z (welfare effects of ceteris paribus changes in ϕ_Y)



Notes: Second-order approximation to the unconditional welfare of savers and borrowers as well as to the unconditional social welfare under welfare criterion "B" for CBDC quantity rule (i) as a function of policy parameter ϕ_Y, for alternative values of the elasticity of substitution across forms of money, η_z. The starred line refers to the baseline calibration whereas the dotted and dashed lines relate to alternative parameterization scenarios.

Figure D.13: Robustness Checks: θ_b (welfare effects of ceteris paribus changes in ϕ_Y)



Notes: Second-order approximation to the unconditional welfare of savers and borrowers as well as to the unconditional social welfare under welfare criterion "B" for CBDC quantity rule (i) as a function of policy parameter ϕ_Y, for alternative values of the central bank's collateral requirement parameter for government bonds, θ_b. The starred line refers to the baseline calibration whereas the dotted and dashed lines relate to alternative parameterization scenarios.