CBDC and Banks: Threat or Opportunity?

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ABSTRACT

We study how banks react to the introduction of a Central Bank Digital Currency (CBDC) when households have heterogeneous preferences. We find that banks increase their deposit interest rates in response to a CBDC, even when the CBDC pays no interest rate. However, when the central bank provides funding to offset the loss in deposits, banks optimally push households towards the CBDC by reducing deposit interest rates. This allows them to liquidate reserves, reduce their cost of funding, and increase their profits. We calibrate the model to provide quantitative estimates of these mechanisms.

Keywords: CBDC, disintermediation, banks, monetary policy.

JEL classification: E42, E58, G21, G28.

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1 Introduction

A Central Bank Digital Currency (CBDC) is a *digital representation of a sovereign currency, issued by and as a liability of a jurisdiction's central bank or other monetary authority.*[1] As households will exchange bank deposits for CBDC, disintermediation risk is the primary concern of academics and policymakers. Banks will need to seek new funding sources, possibly leading to adverse real effects (Fernández-Villaverde, Sanches, Schilling, and Uhlig, 2020). Neutrality in this context is attainable only assuming perfect substitutability between CBDCs and bank deposits, with the central bank compensating for the lost deposits (Brunnermeier and Niepelt, 2019). However, perfect substitutability between CBDCs and traditional bank deposits is unlikely, given the heterogeneous households' reactions to the unique technological and institutional features of the CBDC (Bijlsma, van der Cruijsen, Jonker, and Reijerink, 2021).

This paper explores the optimal responses of the banking sector to the introduction of an imperfect-substitute, interest-bearing CBDC under different central bank policies to avoid disintermediation. We use a two-period partial-equilibrium model where households have a heterogeneous preference for a CBDC, modeled as a convenience yield. We find that for low CBDC interest rates, banks take advantage of the CBDC by unloading excess reserves. For increasingly higher CBDC interest rates, commercial banks increase deposit interest rates to retain depositors. However, when the central bank compensates the lost deposits, commercial banks optimally push households toward the CBDC by reducing deposit rates, instead of increasing them. This response allows them to profit from the CBDC convenience yield. Our results are robust to different refinancing rates.

To investigate the responses of commercial banks to the introduction of a CBDC, we develop a two-period model where the commercial bank intermediates between households and entrepreneurs and maximizes its profits by choosing the interest rate on deposits and the risk level of its loans. Households receive an initial endowment and can hold either bank deposits, bank equity, CBDC, or choose an outside storage technology. Households' demand for CBDC depends on the CBDC interest rate plus an heterogeneous convenience yield that captures the non-pecuniary value of holding a CBDC with respect to bank deposits. This convenience yield represents the households' heterogeneous preferences for different CBDC features, such as a new payment technology (e.g.,

[1] Kiff, Alwazir, Davidovic, Farias, Khan, Khiaonarong, Malaika, Monroe, Sugimoto, Tourpe, and Zhou (2020).

programmable money, free and instantaneous cross-border payments, etc.) or additional safety (i.e., issued by central bank, no limit on deposit guarantee). We calibrate a baseline model without CBDC on US data over the period 2009-2020, and then we introduce CBDCs with different designs to run counterfactual experiments. While our setting does not capture general equilibrium mechanisms, it allows substantial flexibility in modeling the CBDC and to obtain quantitative predictions of the bank's response to different levels of CBDC interest rates, distributions for the CBDC convenience yield, and central bank funding mechanisms.

We first introduce an interest-bearing CBDC in a setting in which the central bank does not compensate the bank for the loss in deposits. When there is no convenience yield for CBDC, households choose between bank deposits and CBDC only by comparing the respective interest rates. This scenario presents corner solutions. Whenever the deposit interest rate is higher than the CBDC one, no households hold CBDC and the bank is not affected. Conversely, when the CBDC interest rate is higher, all households shift to CBDC, with the bank eventually closing.[2] When households have a preference for CBDC, we observe that, already for low CBDC interest rates, the commercial bank facilitates the drain of deposits by not increasing its deposit rate. This response allows the bank to offload its excess reserves by using them to accommodate households' switch to CBDC (as in Fraschini, Somoza, and Terracciano, 2023), hence increasing its profitability. When the households' demand for CBDC is higher than the amount of excess reserves, the bank competes for deposits by increasing interest rates, which translates into riskier loans and lower profitability.

Next, we focus on the case in which the central bank refinances the commercial bank to compensate for the loss in deposits. Specifically, we investigate the cases in which the central bank applies a funding interest rate equal to the optimal deposit interest rate in the economy without a CBDC, the optimal deposit rate in the economy with a CBDC, the interest rate on reserves, and the CBDC interest rate. In each scenario, the commercial bank can borrow from the central bank up to the amount of CBDC in circulation, but less than its loss in deposits. We find that the commercial bank never tries to retain deposits by increasing the interest rate. On the contrary, in addition to offloading reserves as in the scenario without funding, it reduces deposit rates even

[2]Note that there is no wholesale funding in the model. The presence of wholesale funding would prevent the foreclosure of the bank.

further for higher CBDC interest rates. The quantity of deposits and central bank funding the bank can attain is always sufficient to satisfy its funding needs. As the CBDC convenience yield attracts some of those households that would have preferred an outside storage technology, the commercial bank can offer a lower deposit interest rate while obtaining an optimal amount of funding. These mechanisms are common across all considered scenarios.

Finally, we calibrate households' CBDC convenience yield using survey data from Bijlsma et al. (2021). Specifically, we take the extensive margin variation of any household willing to hold CBDC for given spreads between CBDC and deposit interest rates. With the estimated distribution, we reproduce our main analysis and find that a CBDC that pays no interest rate would cause a reduction in deposits by -10.91%, with a small decrease in the bank deposit rate.

Our findings contribute to the current debate about CBDC issuance by providing two practical policy implications. First, the introduction of a CBDC, even with no interest rate, can affect bank behavior significantly, for instance by pushing them to reduce deposit interest rates in order to offload reserves. Our results underscore the need for central banks to carefully design CBDC features and policies to mitigate potential unintended consequences. Second, the compensation mechanism whereby the central bank channels funds back to commercial banks in response to CBDC adoption plays a crucial role. It can create a balance that prevents excessive shifts in household deposits, ensuring financial stability. However, this mechanism allows banks to increase their profits by exploiting households' preference for a CBDC. Overall, our results highlight the delicate balance that needs to be struck in CBDC design to achieve the desired financial stability and efficiency gains, without disproportionately benefiting or harming any particular sector.

Related literature. Our paper contributes to the strand of the literature on CBDC that focuses on the banks' responses to its introduction in the economy. Specifically, we employ a banking model to investigate how banks strategically react to CBDC deposit competition to finance their loans. Whited, Wu, and Xiao (2022) use a dynamic structural model to quantify the changes in bank lending to the introduction of a CBDC and find that it falls by one-fourth of the drop in deposits due to incomplete resort to wholesale funding. Kumhof and Noone (2018) discuss the implications for financial stability and disintermediation risk. They conclude that a set of principles should be followed in designing a CBDC, among which there should not be any guarantee of on-demand convertibility of bank deposits. More generally, Brunnermeier and Niepelt (2019) develop the theoretical conditions to achieve neutrality (i.e., the same equilibrium allocations) between private and public money.

We also refer to the branch of literature that deals with the monetary policy implications of a CBDC. Meaning, Dyson, Barker, and Clayton (2021) discuss how each monetary policy transmission mechanism would be impacted by a CBDC and conclude that monetary policy would not significantly change its functioning. Fernández-Villaverde et al. (2020) and Fernández-Villaverde, Schilling, and Uhlig (2021) use a modified version of the model by Diamond and Dybvig (1983), with a central bank that engages in large-scale intermediation by competing with private financial intermediaries for deposits and investing in long-term projects. They find that the set of allocations achieved with private financial intermediation can also be achieved with a CBDC, and that the central bank is more stable than the commercial banking sector during a panic. Thus, they conclude that the central bank would arise as a deposit monopolist. Piazzesi, Rogers, and Schneider (2022) develop a New Keynesian model with a banking system and consider a setup where everyone has deposit accounts at the central bank, which controls both the nominal quantity and the interest rate. Chiu, Davoodalhosseini, Jiang, and Zhu (2020) take a different approach and develop a micro-founded general equilibrium model with money and banking. They show that when banks have no market power, issuing a CBDC would crowd out private banking. However, when banks have market power in the deposit market, a CBDC with the proper interest rate would encourage banks to pay higher interest or offer better services to keep their customers. Nevertheless, our results suggest that this might not be the case when the central bank passes through CBDC funding. Finally, Niepelt (2024) studies how CBDC and bank reserves influence market power and liquidity transformation. He shows how CBDC provides liquidity more efficiently unless the central bank refinances banks. Overall, we contribute to this strand of literature by studying the case in which the central bank compensates the banking sector for lost deposits.

The rest of the paper is organized as follows. Section 2 presents the baseline model without CBDC, Section 3 shows the calibration of the model on US data, Section 4 designs the CBDC in our model, Section 5 presents the results of the counterfactual exercises, Section 6 provides quantitative implications, and Section 7 concludes.

2 Baseline Model Without CBDC

Before introducing and analyzing the effects of a CBDC, we develop a partial equilibrium model of the banking sector, that we calibrate on US data in Section 3.

We consider a representative commercial bank that operates over 2 periods and intermediates between entrepreneurs and households. At time 0, the bank chooses the interest rates on deposits and the risk of the entrepreneurs' projects to maximize its profits in the next period. The central bank regulates the banking sector and conducts monetary policy. Figure 1 outlines the structure of the baseline model, representing the relations between entrepreneurs, households, commercial bank, and central bank.

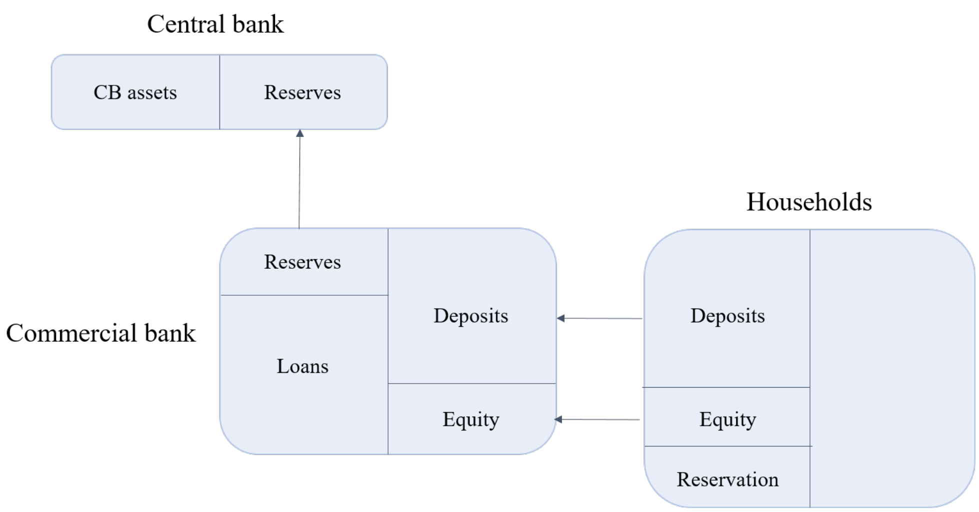

Figure 1. The figure illustrates the baseline model of the banking sector. The bank intermediates between entrepreneurs and households. Entrepreneurs are represented by a production function. Households put their savings either in bank deposits, bank equity, or in an outside storage technology. The bank chooses the interest rates on deposits and the loans' level of risk. The central bank regulates the commercial bank.

2.1 Households

A unit mass of risk-neutral households is endowed with one unit of good at time 0. They can choose to supply their endowment to a bank, in form of deposits or equity, or an outside storage technology. Since banks can minimize monitoring costs more efficiently, as in Diamond (1984), there is no benefit for households to fund entrepreneurs directly. The return on bank equity r^E is higher than the interest rate on deposits r^D, but deposits are insured and the bank can limit the amount of equity in circulation. For these reasons, households have an incentive to hold deposits.

Each household has access to an outside storage technology that yields $1+\theta_i$, where the reservation value $\theta_i \in \left[\underline{\theta}, \overline{\theta}\right]$ is drawn from the distribution function Θ and is private information to each household. We can interpret this alternative saving option as a deposit outside the banking sector that pays θ_i, or as either cash or consumption where the reservation value represents the convenience yield of using cash or consuming at time 0.

If $r^D = \theta_i$, then a household would be indifferent between saving with bank deposit and using the outside storage technology. We can assign such households to a bank. The supply of deposits is the sum of all households for which the interest rate offered by the bank is higher than the reservation value:

$$D\left(r^D\right) = \int_{\underline{\theta}}^{\overline{\theta}} \mathbb{1}_{\theta_i \leqslant r^D} \; d\Theta. \tag{1}$$

We can easily prove that $\frac{\partial D(r^D)}{\partial r_t^D} > 0$, meaning that households are better off the higher the interest rate paid by the bank. For simplicity, we assume Θ to be a uniform distribution of type $\mathcal{U}\left(\underline{\theta}, \overline{\theta}\right)$. In this case, the supply for deposits can be simplified to:

$$D\left(r^D\right) = \begin{cases} 0, & r^D < \underline{\theta} \\ \frac{r^D - \underline{\theta}}{\overline{\theta} - \underline{\theta}}, & \underline{\theta} \leq r^D \leq \overline{\theta} \\ 1, & r^D > \overline{\theta} \end{cases}. \tag{2}$$

If we visualize the distribution of reservation values as the line in Figure 2, all households with θ_i lower than r^D hold deposits, while the ones just above hold equity and the rest hold the outside storage technology. We define r^θ as the maximum reservation value that the bank needs to match to attract the necessary amount of equity and deposits.[3] The following condition ensures that bank equity is more attractive than the outside storage technology:

$$r^\theta \leq r^E, \tag{3}$$

[3] The maximization problem of the bank determines the ratio of equity and deposits. For this reason, we explicitly define the functional form of r^θ in equation (10).

while the following that deposits and equity never exceed the amount endowed to households:

$$r^{\theta} \leq \overline{\theta}. \tag{4}$$

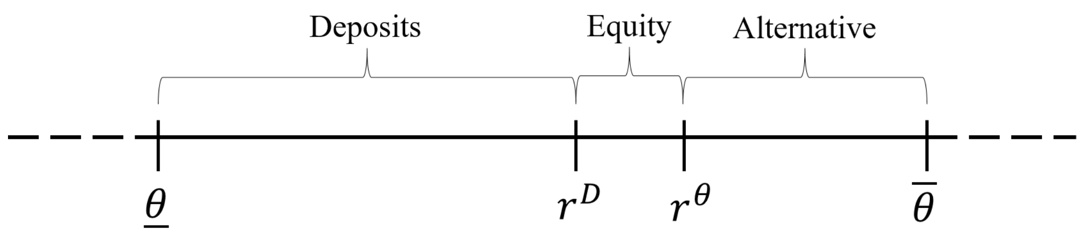

Figure 2. The figure represents the function for the supply of deposits, where $\underline{\theta}$ is the minimum household reservation value, $\overline{\theta}$ the maximum, r^D the interest rate on bank deposits and r^{θ} the maximum reservation value that the bank needs to match to attract the necessary amount of equity and deposits.

2.2 Entrepreneurs

At time 0, the entrepreneurs receive an amount L of loans from the bank to fund their risky projects. In the second period, the projects are successful with probability p. With probability $1-p$ the projects fail, and entrepreneurs do not repay the bank. In case of success, the entrepreneurs repay L^{α}, where α is the output elasticity. With this functional form, the marginal productivity is always positive but declining, meaning that as the initial investment increases, the output increases as well but at a diminishing rate.

2.3 Central Bank

The central bank regulates the banking sector and conducts monetary policy. It sets the liquidity and capital requirement for the representative commercial bank. Since we do not distinguish between short- term and long-term maturities, we interpret the liquidity requirement as a constraint on reserves: the commercial bank must hold at least δ of its deposits in reserves at the central bank. Moreover, because of moral hazard, the central bank requires the commercial bank to finance at least κ of its loans with equity.

The commercial bank's reserves are liabilities on the central bank's balance sheet that can be remunerated. Under normal circumstances, the only reserves held at the central bank are the mandatory ones, and they are usually backed by safe assets (short-term government bonds).[4] After the global financial crisis in 2008, major central banks decided to implement a new type of monetary policy called quantitative easing (QE). The new monetary policy has been implemented in a low interest rate environment by purchasing longer-term government bonds or corporate bonds from other financial institutions in exchange for newly created reserves. While purchasing these securities, the central bank increases their prices and lowers their interest rates, boosting spending in the economy. The central bank sets the interest rate on reserves r^M, using it as a monetary policy tool.

2.4 Commercial Bank

The representative commercial bank intermediates between entrepreneurs, that need loans to fund their projects, and households, that hold part of their savings in the form of deposits or invest in bank equity. The bank maximizes its profits by choosing the interest rates on deposits and the probability of success of the entrepreneurs' projects. The interest rate on deposits at equilibrium is such that the demand from the bank meets the supply from households, to avoid credit rationing that is never optimal.

We define the profits of the bank in a context of limited liability. With probability of success p, the loans yield L^α and the bank repay households' deposits, otherwise entrepreneurs fail and the bank does not repay its stakeholders. In case of bankruptcy, there is no government intervention to save the bank, but households will receive the payment on their deposits thanks to a government insurance. The partial equilibrium model depicted in this paper does not focus on these mechanisms.

We define the amount of reserves held at the central bank as a fraction of deposits:

$$M\big(r^D\big) = \delta D\big(r^D\big)\,, \tag{5}$$

where δ is the liquidity requirement set by the central bank. Under quantitative easing, the central bank creates new reserves to back the asset-purchase programs. We simplify this mechanism by setting a higher liquidity requirement for banks, so that this constraint is always binding. As equity

[4] Here, we consider a partial equilibrium without modelling the market for government bonds. Please, refer to Fraschini et al. (2023) for a general equilibrium analysis with implications for the amount of government bonds in circulation.

is more costly than deposits, the capital requirement is also always binding:

$$E = \kappa L. \tag{6}$$

The amount of loans invested in risky projects is given by the balance sheet identity:

$$L\big(r^D\big) = D\big(r^D\big) + E - M\big(r^D\big) = \big(1-\delta\big)\frac{1}{1-\kappa}D\big(r^D\big)\,. \tag{7}$$

In the second period, with probability p, the bank receives payments on its loans from the entrepreneurs and on its reserves from the central bank, and it pays the interest on deposits to households. The bank's profit is:

$$\pi\big(r^D, p\big) = p\Big[\,\big[L\big(r^D\big)\big]^{\alpha} + (1+r^M)M\big(r^D\big) - (1+r^D)D\big(r^D\big)\,\Big] - \frac{1}{2}c\,p^2, \tag{8}$$

where c captures the risk-return payoff of the entrepreneurs' projects. Such a cost discourages the bank from choosing projects that have a high probability of success.

The return on equity is defined as the profit for each unit of equity:

$$r^E\big(r^D, p\big) = \frac{\pi\big(r^D, p\big)}{E(r^D)} - 1. \tag{9}$$

We define the maximum reservation value that the bank needs to match to attract the necessary amount of equity and deposits, r^θ, by keeping the same ratio of equity and deposits on the distribution of reservation values:

$$r^\theta\big(r^D\big) = r^D + \big(r^D - \underline{\theta}\big)(1-\delta)\frac{\kappa}{1-\kappa}, \tag{10}$$

where $(r^D - \underline{\theta})$ represents the fraction of reservation values of households that are willing to hold deposits as in Figure 2, and $(1-\delta)\frac{\kappa}{1-\kappa}$ is the ratio of equity over deposits.

Finally, the bank maximizes its profits, by choosing the deposit interest rate and the projects' probability of success. Rewriting all the elements on the bank's balance sheet as functions of deposits, the maximization problem of the bank is:

$$\max_{r^D, p} \; p\left[\left[\big[1-\delta\big]\frac{1}{1-\kappa}D(r^D)\right]^{\alpha} + \big[1+r^M\big]\delta D(r^D) - \big[1+r^D\big]D(r^D)\right] - \frac{1}{2}c\,p^2, \tag{11}$$

such that conditions (3) and (4) are satisfied.

3 Model Calibration

To bring our model to the data, we divide our identification strategy into two steps. The first step consists in calibrating a set of parameters that we can directly pin down from the data. The second step consists in estimating the remaining parameters by matching relevant model outcomes with the data. Since the representative bank in our model portrays the entire banking sector, we use aggregate data for US commercial banks between 2009 and 2020 included.

We pin down three parameters from the data. For the liquidity requirement δ, we use the ratio of commercial banks' reserves to deposits. Such ratio differs from the Basel III guidelines, as it captures the amount of reserves injected by the central bank into the banking system. It is worth pointing out that such reserves can only be exchanged between depository institutions. Hence, the total amount of reserves held by all banks is quasi-exogenous from the point of view of the banking sector. Such reserves are the byproduct of asset-purchase programs and are bound to remain on banks' balance sheets until the central bank decides to absorb them back. For the capital requirement κ, we use the ratio of equity to assets. Basel III capital requirements depend on different risk-weighted quantities that are not featured in our model for simplicity. Therefore, we take as always-binding capital requirement the ratio of overall assets to equity in the data. The interest rate on reserves is unequivocal, especially since the FED removed reserve requirements thus making all reserves *excess* reserves. Finally, we assume that the households' minimum reservation value is zero, as in Corbae and D'Erasmo (2021).

Table 1
The table shows the values of the model parameters that we directly pin from the data or the extant literature.

Par.	Definition	Value	Source
δ	Ratio reserves to deposits	0.1727	FRED
κ	Ratio equity to assets	0.1191	FRED
r^M	Reserve interest rate	0.0065	FRED
$\underline{\theta}$	Min household reservation	0	Corbae and D'Erasmo (2021)

For the second step, we select relevant model outcomes for each parameter we need to estimate. We estimate the loans' output elasticity α by looking at the return on equity. The parameter α affects the loans' profitability and hence the return that the bank can extract from its loans. We match the loan delinquency rate for the risk-return payoff c in our model. This parameter directly impacts the optimal amount of risk that the bank chooses for its loans, and therefore the delinquency rate. Finally, we estimate $\overline{\theta}$ by matching the interest rate on deposits. The higher the maximum reservation value, the higher the interest rate that the bank has to offer in order to attract deposits. Table 2 shows the parameter values that minimize the distance between the target and estimated model outcomes. In Appendix A, we show the model outcomes' sensitivity to changes in the parameters.

Table 2
The table shows the values of the model parameters that we calibrate targeting specific model outcomes.

Par.	Definition	Value	Outcome	Target (FRED)	Estimate
α	Loans output elasticity	0.7744	Return on equity	0.0864	0.0864
c	Risk-return payoff	0.1466	Loan delinquency rate	0.0352	0.0370
$\overline{\theta}$	Max household reservation	0.013	Deposit interest rate	0.0072	0.0073

4 Model with CBDC

We introduce a CBDC in the baseline model calibrated in Section 3 with aggregate US data over the period 2009-2020. We model the CBDC as a direct liability of the central bank as shown in Figure 3. In line with current working hypotheses,[5] we assume that a CBDC can pay an interest rate r^C, that is exogenously set by the central bank.

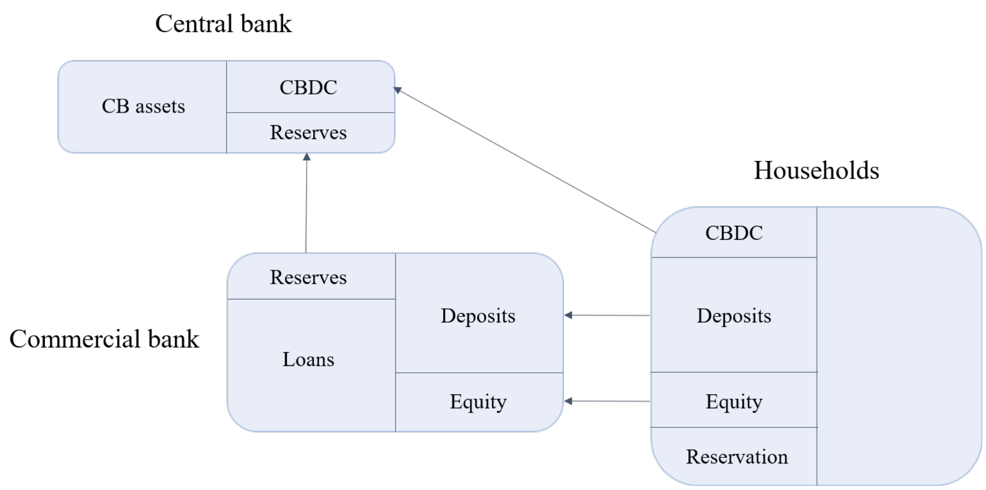

Figure 3. The figure shows a stylized representation of the baseline model presented in Section 2 with the addition of a CBDC. Households have the choice between bank deposits, bank equity, outside storage technology (reservation), and CBDC.

While we are agnostic concerning the exact characteristics of the technology underlying a CBDC, we assume that a certain share of the population will prefer such technology and extract utility from it for different reasons. For example, one reason could be that a CBDC would introduce an element of technological innovation with features like money programmability, instantaneous settlements, smart contracts, and decentralized financial services. Moreover, as a CBDC is issued by the central bank, it could provide a safe and trustworthy instrument to citizens. Finally, policymakers ensure the interoperability of the CBDC with other means of payments or saving instruments without the purpose of substituting them, so that households will be at worst indifferent. Therefore, in the model, we assume that households have a heterogeneous preference for CBDC. Each household has a preference for the new technology $\gamma_i \in [\underline{\gamma}, \overline{\gamma}]$, that is drawn from the distribution function Γ. For the sake of simplicity, we assume that the preference for the new technology can be expressed as a convenience yield, to be added on top of r^C, and compared against the interest rate on deposits r^D

[5] See BIS (2020) or ECB (2020), for example.

and the household's reservation value θ_i. Each household's CBDC convenience yield is randomly drawn and independent of the reservation value. The bank deposit supply is the following:

$$\tilde{D}\left(r^D\right) = \int_{\underline{\gamma}}^{\overline{\gamma}} \int_{\underline{\theta}}^{\overline{\theta}} \mathbb{1}_{\{r^C+\gamma_i \leqslant r^D\}} \mathbb{1}_{\{\theta_i \leqslant r^D\}} \, d\Theta \, d\Gamma, \tag{12}$$

meaning that households prefer bank deposits if the interest rate offered by the bank is higher than their reservation value and the CBDC interest rate adjusted for the preference. Similarly, the CBDC supply is the sum of all those households for which the preference-adjusted CBDC interest rate is higher than the deposit interest rate and the reservation value:

$$\tilde{C}\left(r^D\right) = \int_{\underline{\gamma}}^{\overline{\gamma}} \int_{\underline{\theta}}^{\overline{\theta}} \mathbb{1}_{\{r^C+\gamma_i > r^D\}} \mathbb{1}_{\{r^C+\gamma_i > \theta_i\}} \, d\Theta \, d\Gamma. \tag{13}$$

4.1 CBDC Introduction Mechanism

When we introduce a CBDC in the economy, and households want to transfer part of their savings from bank deposits to CBDC, the commercial bank accommodates this reallocation of funds by transferring resources to the central bank. Fraschini et al. (2023) shows that it is optimal for the bank to reduce its reserves, up to the amount lost, because reserves are less remunerated than loans. The underlying mechanism is similar to what happens when households withdraw cash at an ATM. The commercial bank reduces the household's bank deposit and transfer the same amount of reserves to the central bank in exchange for banknotes that will give to the household. The transfer of savings from bank deposits to CBDC will work in a similar way, as long as reserves are available.

To quantify the amount of savings transferred from the bank to CBDC, we compare the new deposit supply in equation (12), with the equilibrium amount of deposits D_{cal} in the baseline model without CBDC calibrated in Section 3. If there is no loss of funds, and $D_{cal} - \tilde{D}\left(r^D\right) \leq 0$, then the maximization problem of the bank remains unchanged as in Section 2. When households move funds outside the banking sector, it means that they prefer either the CBDC or the outside storage technology. We define the bank's transfer as:

$$\tilde{\tau}\left(r^D\right) = \min\left\{ D_{cal} - \tilde{D}\left(r^D\right); \tilde{C}\left(r^D\right) \right\}, \tag{14}$$

where the minimum ensures that we do not consider a reduction in deposits in favour of the outside storage technology. The reduction in reserves that accommodates this transfer is:

$$\Delta\tilde{M}\left(r^D\right) = \tilde{\tau}\left(r^D\right) + \delta\left(D_{cal} - \tilde{D}\left(r^D\right) - \tilde{C}\left(r^D\right)\right)\mathbb{1}_{\left\{D_{cal}-\tilde{D}(r^D)>\tilde{C}(r^D)\right\}}, \tag{15}$$

where the second term comes into play whenever there is a loss in deposits in favour of the outside storage technology.

However, the decrease in reserves $\Delta\tilde{M}$ is possible only when there are excess reserves available. The central bank can impose a liquidity buffer ι representing the minimum fraction of reserves the bank can hold, that can be different from the liquidity requirement δ. The difference between ι and δ becomes relevant in a quantitative easing scenario, when the banking sector is injected with a lot of liquidity coming from the asset-purchase programs, with the total amount defined by δ. Since banks can use the CBDC to reduce their excess reserves, we need a different liquidity buffer ι, that for simplicity, we set to 0.[6] Therefore, in an economy with CBDC, the bank reserves become:

$$\tilde{M}\left(r^D\right) = \max\left\{M_{cal} - \Delta\tilde{M}\left(r^D\right); \, \iota\tilde{D}\left(r^D\right)\right\}, \tag{16}$$

where M_{cal} is the amount of reserves in the baseline model without CBDC calibrated in Section 3.

If the amount of savings that households want to transfer from bank deposits to CBDC is higher than the liquidity buffer, the central bank can compensate for the additional loss in deposits by rechannelling funds back to the banking sector. The bank can choose the amount F to borrow from the central bank as long as it is lower than the amount of deposits lost after exhausting the excess reserves:

$$\overline{F}\left(r^D\right) = \tilde{\tau}\left(r^D\right) - M_{cal} + \iota\tilde{D}\left(r^D\right). \tag{17}$$

The central bank charges the commercial bank an interest rate r^F for this type of funding. In Section 5, we consider different policies for the funding interest rate r^F.

[6] We could set a $\iota > 0$ in the future to improve the tightening elasticity of the central bank's balance sheet.

4.2 Bank's Maximization Problem

When the commercial bank maximizes its profits, it considers the amount of central bank funding as an additional choice variable. The composition of its balance sheet change to include this new type of liability, as shown in Figure 4.

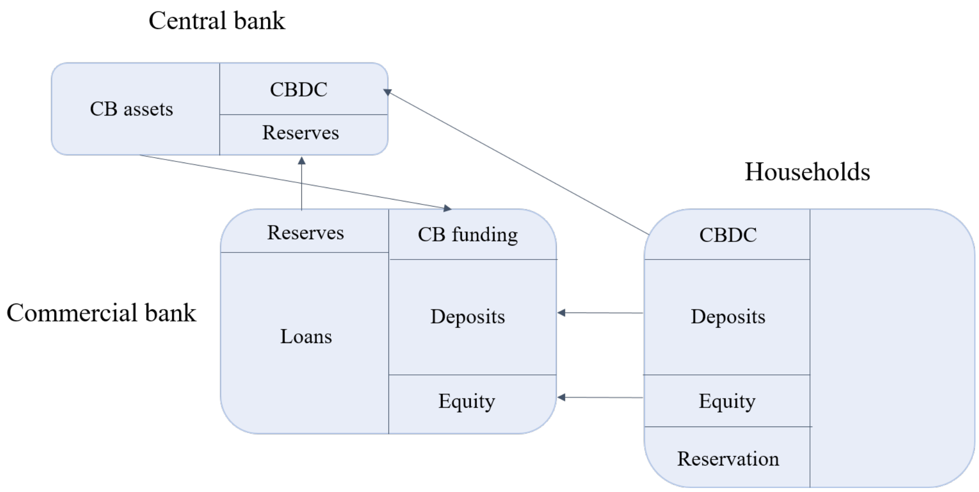

Figure 4. The figure shows a stylized representation of the baseline model presented in Section 2 with the addition of a CBDC and the central bank refunding mechanism. Households have the choice between bank deposits, bank equity, outside storage technology (reservation) and CBDC. The commercial bank can decide to borrow from the central bank to compensate the loss in deposits.

While the capital requirement is still binding, as in equation (6), the amount of loans is given by the following identity:

$$\tilde{L}\left(r^D, F\right) = \frac{1}{1-k}\left[\tilde{D}\left(r^D\right) - F - \tilde{M}\left(r^D\right)\right]. \tag{18}$$

The maximization problem of the bank is:

$$\max_{r^D,\, p,\, F}\ \tilde{\pi}\left(r^D, p, F\right) = p\left[\left[\tilde{L}\left(r^D, F\right)\right]^{\alpha} + \left[1+r^M\right]\tilde{M}\left(r^D\right) - \left[1+r^D\right]\tilde{D}\left(r^D\right) - \left[1+r^F\right]F\right] - \frac{1}{2}c\,p^2, \tag{19}$$

such that such that conditions (3) and (4) are satisfied, with

$$\tilde{r}^{\theta}\left(r^D, F\right) = \begin{cases} r^D + \left(r^D - \underline{\theta}\right)\frac{\tilde{E}\left(r^D, F\right)}{\tilde{D}\left(r^D\right)}, & \tilde{D}\left(r^D\right) > 0 \\ \underline{\theta} + \left(\overline{\theta} - \underline{\theta}\right)\tilde{E}\left(r^D, F\right), & \tilde{D}\left(r^D\right) = 0 \end{cases}, \tag{20}$$

and

$$\tilde{r}^E\left(r^D, p, F\right) = \frac{\tilde{\pi}\left(r^D, p, F\right)}{\tilde{E}(r^D, F)} - 1. \tag{21}$$

5 CBDC Effects

The effects of introducing a CBDC in the economy depend on three different design features, namely, the CBDC interest rate, the distribution of households' CBDC convenience yield, and whether we the central bank compensates the commercial bank for the loss in deposits. In this Section, we perform a counterfactual analysis where we investigate these mechanisms by introducing them in the calibrated model. We keep the same parameter estimates obtained in the calibration in Section 3, we introduce a CBDC in the model with the mechanisms described in Section 4, and we study the representative commercial bank's optimal response.

5.1 CBDC Interest Rate

The representative commercial bank chooses the optimal interest rate on deposits and the loans' level of risk considering the fixed CBDC interest rate exogenously set by the central bank. We report our results with respect to the spread between the remuneration on the CBDC r^C and the deposit interest rate in the equilibrium without a CBDC r^D_{cal}. We show how the key model outcomes change with different values of the exogenously-set CBDC interest rate. For each CBDC interest rate considered, the corresponding values for the model outcomes come from a different bank's maximization problem. The solid blue line in Figure 5 represents the effects of introducing a CBDC in the absence of convenience yield.

Without any convenience yield, all households choose between bank deposits and CBDC solely based on the highest interest rate, leading corner solutions. For lower CBDC interest rates, $r^C \leq r^D_{cal}$, it is never optimal for the bank to offer a deposit interest rate different from the one in the calibration equilibrium found in Section 3. In this case, the equilibrium never changes. For $r^C > r^D_{cal}$, the CBDC becomes more convenient than bank deposits. This leads to a collapse of the commercial banking sector: indeed, if the commercial bank decided to offer a higher interest rate, it would receiving more deposits than optimal, hence it would eventually invest in increasingly riskier loans. Of course, in reality banks might decide to pay the same interest rate as the CBDC on their deposits while rationing their quantity. At this stage, we ignore this possibility as it is no longer relevant as soon as there are heterogeneous preferences for CBDC. In Section 5.2, we see that with interior solutions, the commercial bank can always decide to lower the interest rate in order to lower deposits, thus eliminating the need for deposit rationing. Note that, for simplicity, the model abstracts from wholesale funding as in practice it would be hard for banks to fully substitute deposits for wholesale funding without the intervention of the central bank. We discuss the case with central bank funding in Section 5.3.

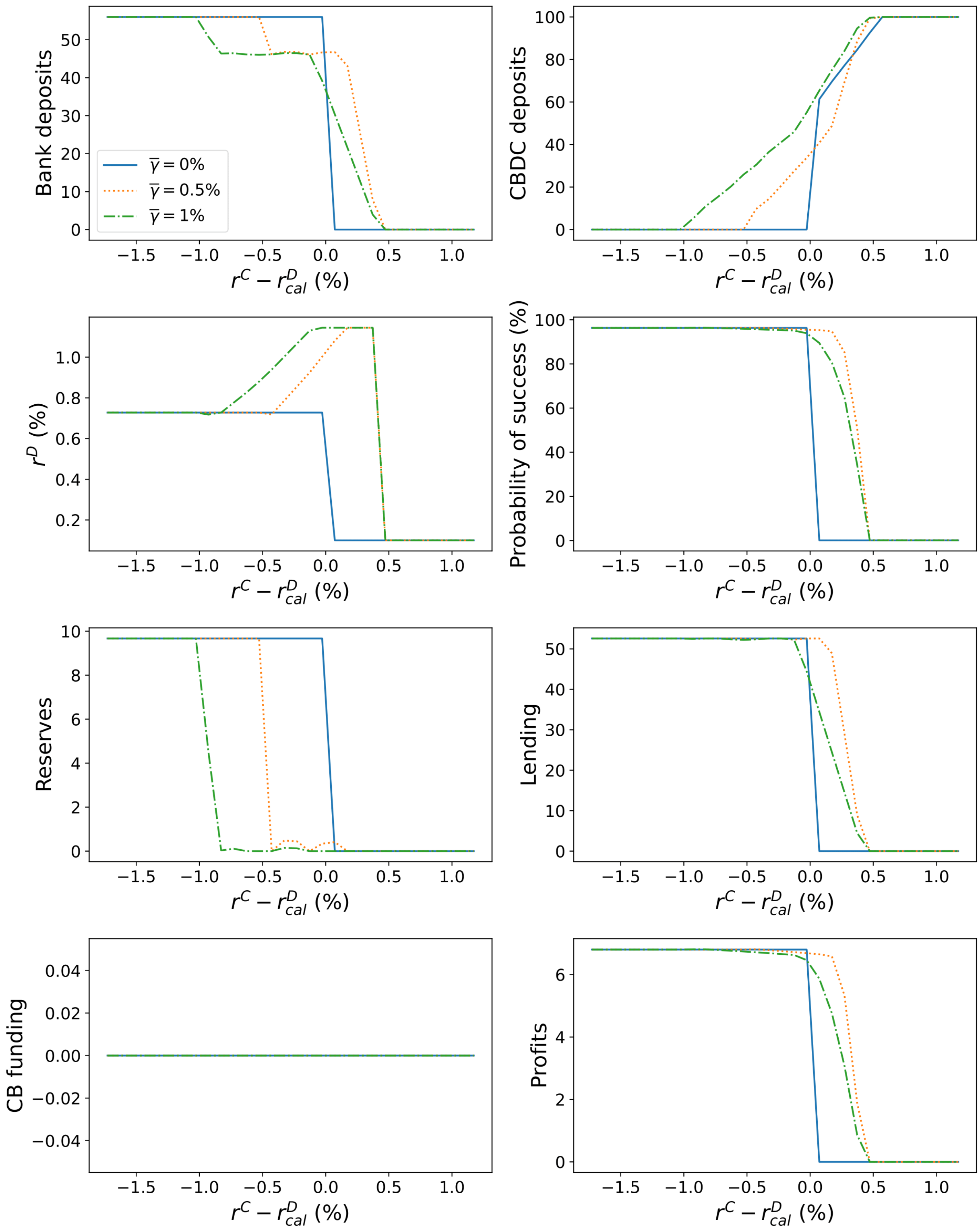

Figure 5. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C and maximum CBDC convenience yield $\overline{\gamma}$. The solid blue line represents the effects of introducing a CBDC in the absence of convenience yield ($\overline{\gamma} = 0\%$). The dotted orange and the dashed green lines represent the effects of introducing a CBDC when households have medium ($\overline{\gamma} = 0.5\%$) and high ($\overline{\gamma} = 1\%$) preference, respectively.

5.2 CBDC Convenience Yield

To highlight the salient economic mechanisms, we assume that each household's CBDC convenience yield is uniformly distributed: $\gamma_i \in \mathcal{U}(0, \overline{\gamma})$. We focus on three levels of maximum convenience yield: null (i.e., $\overline{\gamma} = 0\%$), intermediate (i.e., $\overline{\gamma} = 0.5\%$), and high (i.e., $\overline{\gamma} = 1\%$). When $\overline{\gamma} = 0$, households have no preference for CBDC, and their choice between deposits and CBDC is based solely on the respective interest rates as depicted in Section 5.1. Since the CBCD convenience yield is uniformly distributed, raising $\overline{\gamma}$ mechanically increases the average. Hence, the average CBDC convenience yield is 0.25% in the intermediate case and 0.5% in the high case. Calibrating the value for $\overline{\gamma}$ is challenging as there are not yet large-scale CBDC projects and data. In Section 6 , we use Dutch survey data from Bijlsma et al. (2021) to provide a better estimate of the distribution of γ_i.

The dotted orange and the dashed green lines in Figure 5 represent the effects of introducing a CBDC when households have medium and high preference, respectively.

Notably, for any given r^D, the total amount of deposits (i.e., the sum of bank and CBDC deposits) is mechanically higher when households have access to a CBDC if we assume a positive preference for CBDC. The reason is that there can be households for which r^D is lower than their reservation value, but their CBDC convenience yield is high enough for them to prefer the CBDC over the outside storage technology.[7]

For low r^C, the commercial bank initially favours the adoption of CBDC by refraining from increasing interest rate. The reason lies in the adoption mechanism. When a household buys a unit of CBDC, the bank needs to transfer the deposit to the central bank, that in turns issues a unit of CBDC and credits it to the household. From an accounting perspective such transaction is settled by converting a commercial bank reserve into CBDC, exactly like when a household withdraws cash. Hence, as far as there are excess reserves and they have a low remuneration, the commercial bank uses them to accommodate the reduction of deposits (Fraschini et al., 2023). In this context, such mechanism translates into the commercial bank pushing depositors towards the CBDC as long as it has available reserves and $r^D > r^M$.

Once the reserves are exhausted, the commercial bank starts competing with the CBDC for

[7] Although it is beyond the scope of this paper, this mechanical effect suggests that CBDC might be a useful tool to improve financial inclusion as the total amount of deposits, either with the central bank or the commercial bank, goes up (see Tan, 2023; Andolfatto, 2018, for a more detailed discussion).

deposit funding. Specifically, the commercial bank increases the interest rate on its deposits to make them more attractive to households. With a higher convenience yield on average, the competition starts for lower CBDC interest rates (dashed green line). The reason is that the commercial bank needs to compensate for the higher CBDC convenience yield with higher interest rates on deposits. The increase in the deposit interest rate lead the bank to grant less but riskier loans, with the profits decreasing in the CBDC interest rate up to the point where the bank stops operating. The effect on the quantity of loans is consistent with previous literature (see for instance Whited et al., 2022).

5.3 Central Bank Funding Effects

In this Section, we allow the central bank to compensate the commercial bank for the loss in deposits (as in Brunnermeier and Niepelt, 2019). Such a mechanism is a likely policy for the central bank to prevent the disruption in the lending market shown in the previous Section 5.2.

As mentioned in Section 4, the central bank charges an interest rate r^F when directly lending to the commercial bank. Initially, we set r^F equal to the deposit interest rate that the bank chooses in the equilibrium without CBDC, r^D_{cal}. The idea is that the central bank makes its funding exactly as costly as the commercial banks' funding in the calibration in Section 3. We consider this policy to identify the first-order effects that do not depend on the cost of funding per se.[8] While the central bank sets the interest rate on the funding, we allow the commercial bank to optimally choose the quantity it wants to borrow, conditional on it being lower than the total amount of CBDC in circulation, and less than the difference between their current deposits and the one before the introduction of a CBDC. In other words, the commercial bank can borrow from the central bank up to the amount of deposits lost with the introduction of a CBDC (after exhausting the excess reserves). For the sake of clarity, we present results only for $\overline{\gamma} = 1\%$.[9] Figure 6 shows the optimal responses with and without central bank funding (solid blue and dashed green line, respectively). Note that the case without central bank funding is the same one already discussed in Figure 5.

[8]We explore alternative specifications later in the Section.

[9]Results for other levels of CBDC convenience yield can be found in Appendix B.

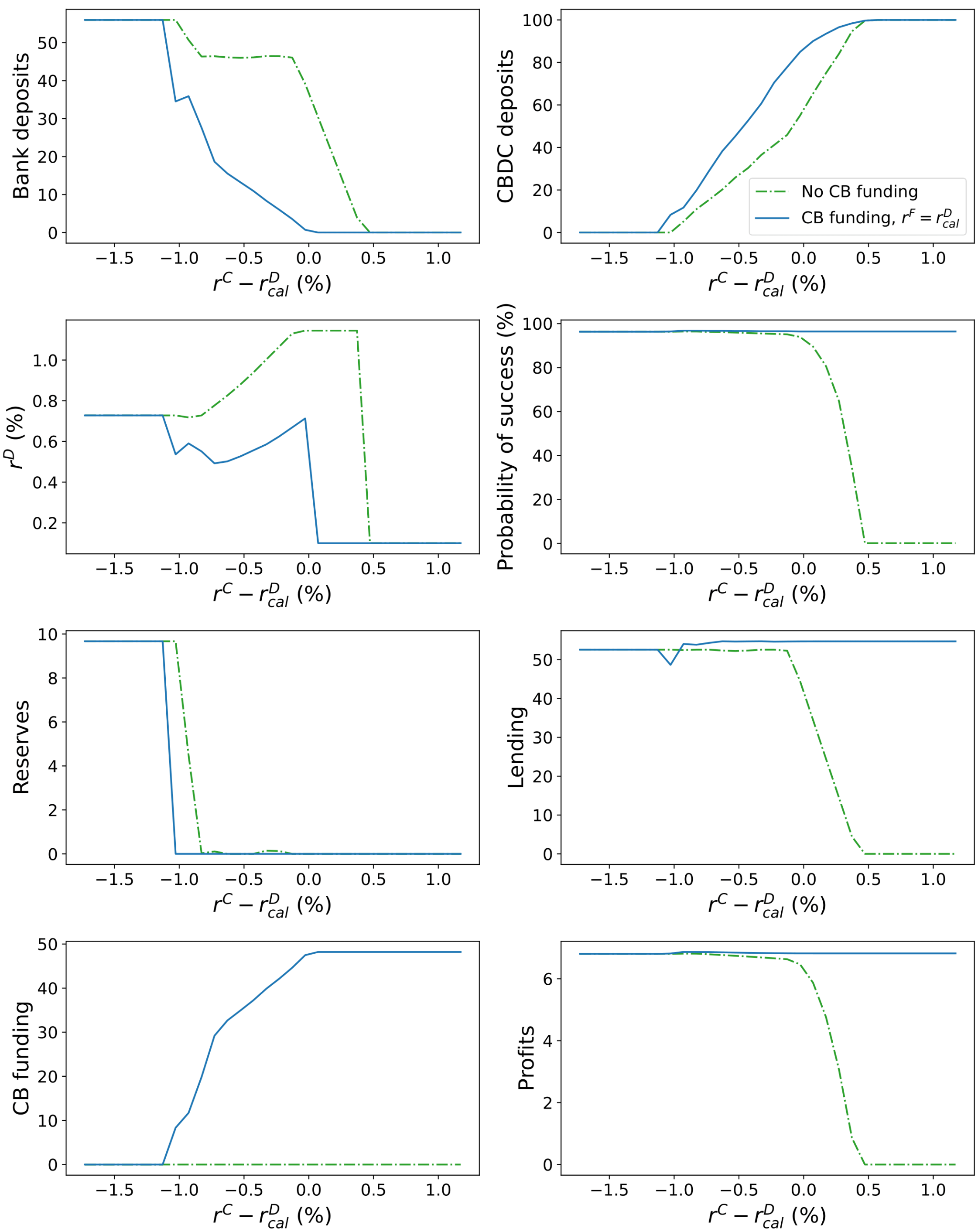

Figure 6. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C with the maximum CBDC convenience yield set to $\overline{\gamma} = 1$. The solid blue line represents the scenario where the commercial bank can borrow from the central bank at $r^F = r^D_{cal}$, which is the deposit rate in the equilibrium without a CBDC. The dashed green line represents the scenario where the commercial bank cannot borrow from the central bank. The bank can borrow up to the amount of CBDC in circulation and less then the loss in deposits due to the introduction of a CBDC.

Once we allow the commercial bank to borrow from the central bank at r^D_{cal} we observe that for every r^C, the interest rates on deposits r^D are lower and CBDC adoption higher. On top of the offload of reserves like in the case without the central bank funding, there is a second mechanism. The CBDC convenience yield drives households' demand for CBDC beyond what would be determined by interest rates alone. At the margin, certain households that would prefer the outside storage technology over the bank deposit choose the CBDC if their convenience yield is high enough. Hence, to maintain an optimal level of deposits, the commercial bank can reduce the interest rate on deposits and compensate for the loss in deposits with the funding from the central bank, whose size is positively impacted by the CBDC convenience yield. In other words, the more households prefer the new technology, the lower the commercial bank cost of funding, even if the central bank sets a relatively high interest rate r^F.

In reality, it would be hard to set $r^F = r^D_{cal}$ for the central bank, as once there is a CBDC, r^D_{cal} is no longer observable. In Appendix B, we expand the analysis by including other policies, i.e., setting the refinancing rate equal to the reserve interest rate ($r^F = r^M$ in Figure 10), the deposit interest rate ($r^F = r^D$ in Figure 11), and equal to the CBDC interest rate ($r^F = r^C$ in Figure 12). Figure 7 shows a comparison of these last three central bank funding policies.

When $r^F = r^M$, we observe the same dynamics as in Figure 6. Nevertheless, we observe that the bank's profits are higher, which is expected as $r^M < r^D_{cal}$. As the CBDC interest rate increases, the deposit interest rate offered by the commercial bank converges to r^M, eventually leading to a permanently higher level of profits and lending, thanks to the cheaper funding.

When the refinancing rate is equal to the deposit rate offered by the bank (i.e., $r^F = r^D$), the dynamics change as the bank's decision on deposits now also sets the cost of funding from the central bank. The commercial bank knows that it will receive financing at the same rate it pays on deposits and sets it to zero as soon as the CBDC becomes attractive enough. Notably, the bank does not set the deposit rate to zero right away because the maximum amount it can borrow from the central bank is equal to the total amount of CBDC deposits. When the CBDC interest rate high enough, the commercial bank permanently increases its profits, while also increasing lending and decreasing risk, as it needs a lower remuneration from its loans. This scenario has important policy implications. Once a CBDC is introduced, counterfactual deposit rates in the absence of a CBDC are unobservable. The central bank can only observe current banks' deposit rates and would likely set r^F accordingly. It is important to remember that in this case the commercial bank would artificially push deposits away and exploit CBDC convenience yields to lower their funding cost. Figure 13 in Appendix B shows the comparison between central bank funding with $r^F = r^D_{cal}$ and $r^F = r^D$.

The last policy we evaluate is the one where the central bank decides to make the CBDC neutral for its income statement by charging the bank the interest rate it pays on CBDC deposits ($r^F = r^C$). For low CBDC interest rates, the effect is the same mechanism as in the previous two cases, with the commercial bank taking advantage of households' CBDC convenience yield and increasing its profits. As CBDC interest rates increase, and thus the central bank funding, the effect on the banking sector becomes negative, with the commercial bank choosing to receive less and less funding and investing in increasingly riskier loans.

Overall, our results suggest that, for CBDC interest rates low enough, the commercial bank can exploit the CBDCs convenience yield to its advantage. Indeed, the commercial bank optimally lowers deposit rates to make the CBDC even more attractive. This response leads to higher margins and consequently higher profits for the bank. Our results also suggest that, if a CBDC has a high convenience yield, it could affect banks' behavior even when it pays no interest rate.

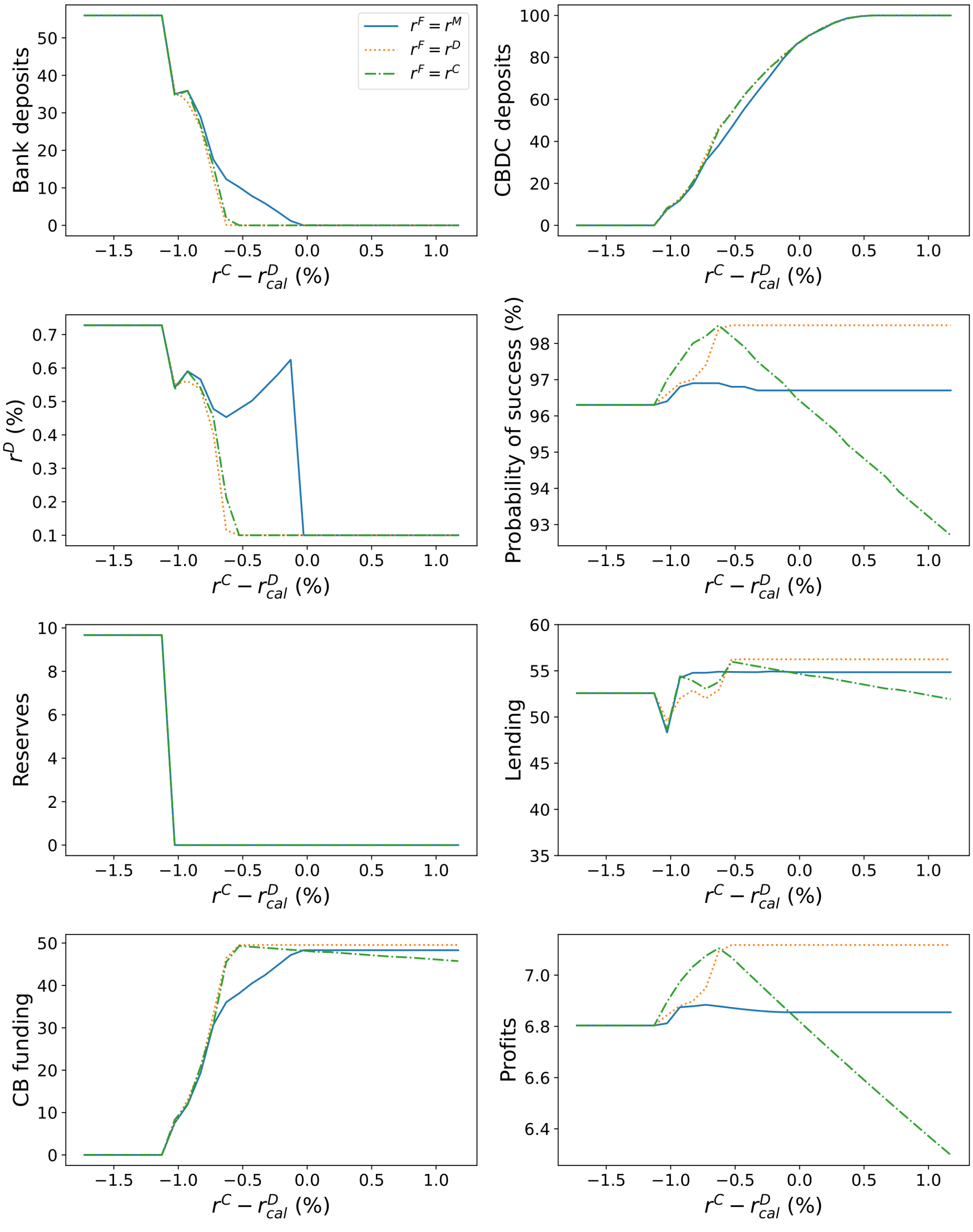

Figure 7. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C with the maximum CBDC convenience yield set to $\overline{\gamma} = 1$. The solid blue line represents the scenario where the commercial bank can borrow from the central bank at r^M, which is remuneration on central bank reserves. The dotted orange line represents the scenario where the commercial bank can borrow from the central bank at r^D, which is the deposit interest rate set by the commercial bank. The dashed green line represents the scenario where the commercial bank can borrow from the central bank at r^C. The bank can borrow up to the amount of CBDC in circulation and less then the loss in deposits due to the introduction of a CBDC.

6 Calibrating the CBDC Convenience Yield

As there exists no large-scale CBDC project, calibrating the convenience yield is a challenging exercise. Nevertheless, having a better estimate of the distribution of γ_i would be informative to measure the magnitude of the effects described in Section 5. For this purpose, we use the survey data collected by Bijlsma et al. (2021).

Bijlsma et al. (2021) surveyed 2,522 Dutch individuals of the CentERpanel aged 16 and over, between 18 December, 2020 and 5 January, 2021. Among the collected data, we focus on the percentage of respondents that would open a CBDC account based on the difference between the remuneration on the CBDC and on the bank deposits, which is exactly what we consider in our model. Specifically, we take the extensive margin variation of any household willing to hold CBDC. We interpret their results as a lower bound for the preference for a CBDC, as the concept is still blurry among the general audience, especially at the time of the survey. Indeed, Bijlsma et al. (2021) report that 53% of the respondents had never heard of CBDC, while another 33% had heard of it but did not know what it is, and only 14% knew about it was meant with CBDC.

For our calibration exercise, we use the percentage of households that would open a CBDC account for every level of $r^C - r^D$, which precisely captures the convenience yield γ_i as defined in Section 4. Table 3 shows the data points.

Table 3

The table shows the data points collected by Bijlsma et al. (2021) that we use to calibrate to distribution of γ_i. For each $r^C - r^D$, the cumulative distribution captures the extensive margin percentage of households that would adopt a CBDC, implicitly pinning down the distribution of the convenience yield γ_i that they would obtain from a CBDC.

$r^C - r^D$	-0.25%	-0.10%	0%	0.10%	0.25%
Cumulative distribution of CBDC adoption	31%	36%	54%	60%	65%

Next, we fit these five data points to a Gaussian cumulative distribution, in order to have a full estimated distribution of γ_i in the population. Figure 8 shows the result. The best fit of our data is a Gaussian distribution with mean $\mu = 0.0098\%$ and $\sigma = 0.5085\%$.

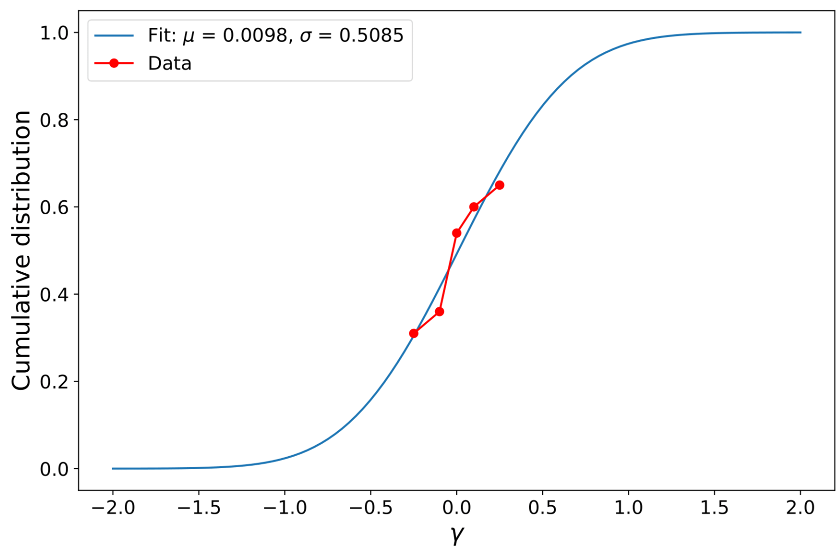

Figure 8. This figure shows the Gaussian cumulative distribution that best fits the data points on CBDC adoption from Bijlsma et al. (2021).

We then substitute the uniform distribution we assumed in Section 5 with the fitted Gaussian distribution and replicate the same counterfactual analysis to obtain plausible quantitative predictions.[10] The only differences we observe from the results obtained in Section 5 are in terms of magnitude. We find that a CBDC with no interest rate would cause a reduction in bank deposits of 11%, lead the commercial bank to decrease deposit rates by 0.02% and increase its profits by 0.24%. The reason is that the bank can accommodate the loss in deposits with a reduction in central bank reserves and hence has no need to compete with the CBDC. Table 4 shows the main results of our model for $r^C = 0$, meaning a non-interest-bearing CBDC.

Table 4

The table shows the model estimates of the impact on banks of a non interest bearing CBDC ($r^C = 0$) when households have heterogeneous preferences, as estimated by Bijlsma et al. (2021). Each column represents a different refinancing rate r^F.

	No CB funding	r^D_{cal}	r^D	r^M	r^C
Δ deposits	−10.93%	−30.70%	−32.77%	−30.99%	−32.61%
Δ r^D	−0.02%	−0.08%	−0.09%	−0.05%	−0.09%
Δ profits	0.24%	1.02%	1.22%	1.13%	1,99%
Δ reserves	−62.95%	−100.00%	−100.00%	−100.00%	−100.00%

[10]The results are reported in Appendix C in Figure 14 and 15.

7 Conclusions

Using a static model of the banking sector, we study banks' response to introducing a CBDC. In our setting, the CBDC provides a convenience yield to households, and it can be interest-bearing. We show that when the central bank does not compensate the commercial bank for the loss in deposits, the latter competes for deposits by raising the deposit interest rate. We find that with a high CBDC convenience yield, the bank would increase deposit rates to secure funding even when the CBDC pays no interest.

The most insightful case is when we allow the commercial bank to borrow from the central bank to offset the loss in deposits. We consider different refinancing rates such as the bank deposit rate, the rate on bank reserves, and the CBDC rate. We find that the bank capitalizes on the heterogeneous convenience yields that households receive from a CBDC by lowering deposit interest rates. This strategy encourages households, especially those with high convenience yields, to switch to CBDC. The reason is that the commercial bank can borrow funds at a lower interest rate, increasing its profitability. Nevertheless, when the refinancing rate is fixed at the rate paid on CBCD deposits, the bank benefits from the introduction of a CBDC only when it pays a relatively low interest rate. When its remuneration starts to increase, bank profitability drops.

These results have important policy implications. When introducing a CBDC, the central bank should be careful about the substitution with bank deposits. If households receive a convenience yield from a CBDC, as expected by policymakers, this could change the incentives of commercial banks and affect them even if the CBDC is not interest-bearing. The interest rate at which the central bank re-channels funding back to the banking sector is crucial. Allowing banks to borrow at low-interest rates would enable opportunistic behaviors by the banking sector, while fixing the refinancing rate to the interest rate on CBDC might jeopardize its profitability and raise financial stability concerns.

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A Sensitivity Analysis

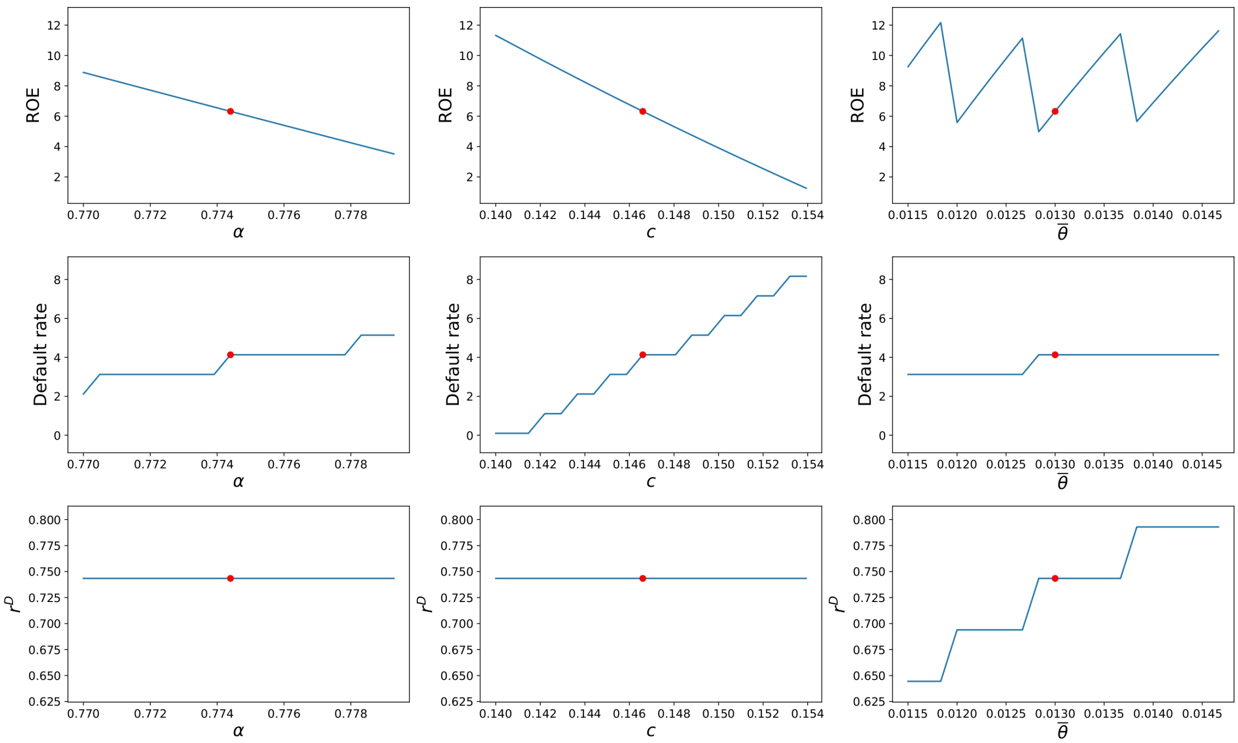

Figure 9. This figure shows the model outcomes' sensitivity to changes in the parameters.

B CBDC With Central Bank Funding

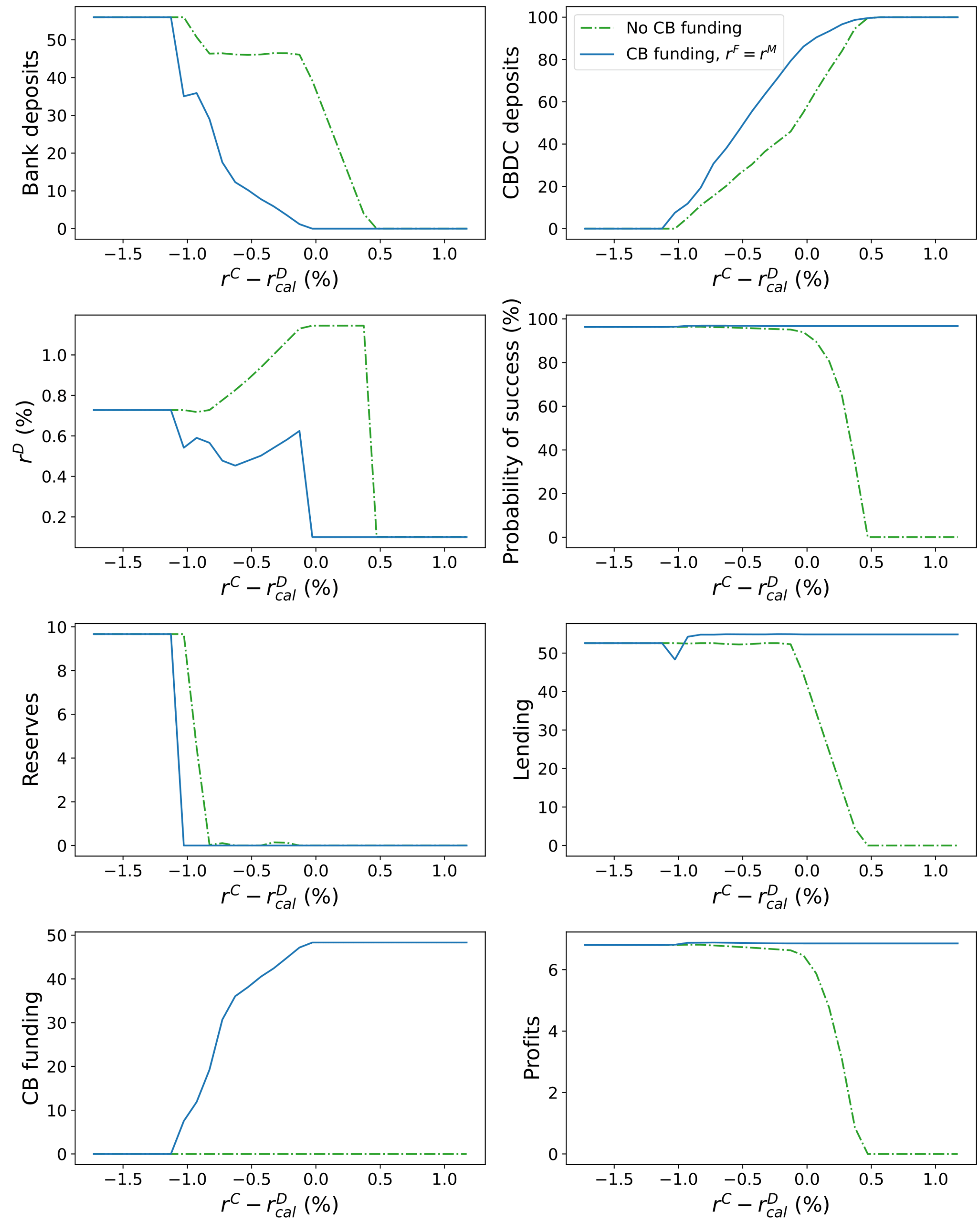

Figure 10. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C with the maximum CBDC convenience yield set to $\overline{\gamma} = 1$. The solid blue line represents the scenario where the commercial bank can borrow from the central bank at r^M, which is remuneration on central bank reserves. The dashed green line represents the scenario where the commercial bank cannot borrow from the central bank. The bank can borrow up to the amount of CBDC in circulation and less then the loss in deposits due to the introduction of a CBDC.

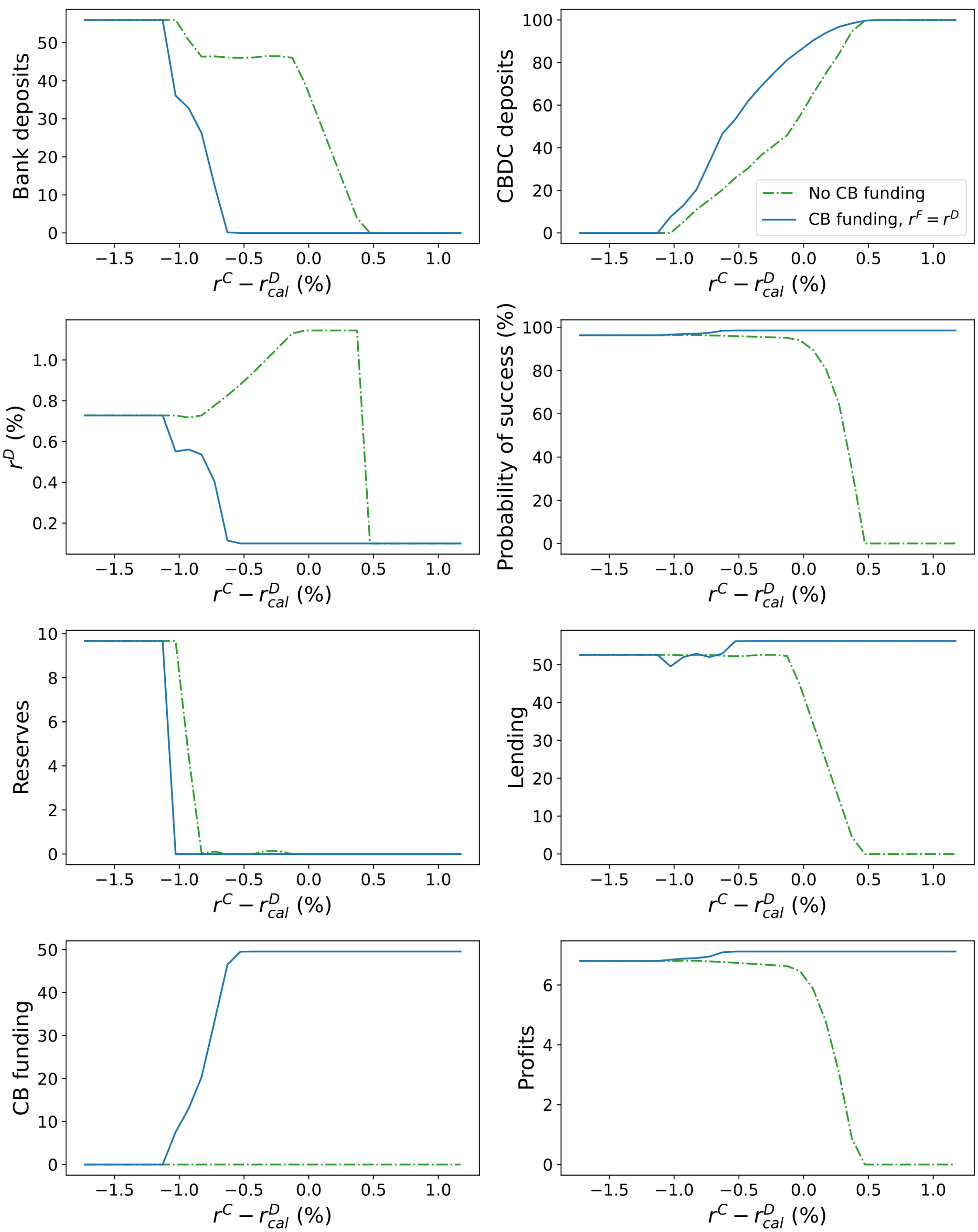

Figure 11. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C with the maximum CBDC convenience yield set to $\overline{\gamma} = 1$. The solid blue line represents the scenario where the commercial bank can borrow from the central bank at r^D, which is the deposit interest rate set by the commercial bank. The dashed green line represents the scenario where the commercial bank cannot borrow from the central bank. The bank can borrow up to the amount of CBDC in circulation and less then the loss in deposits due to the introduction of a CBDC.

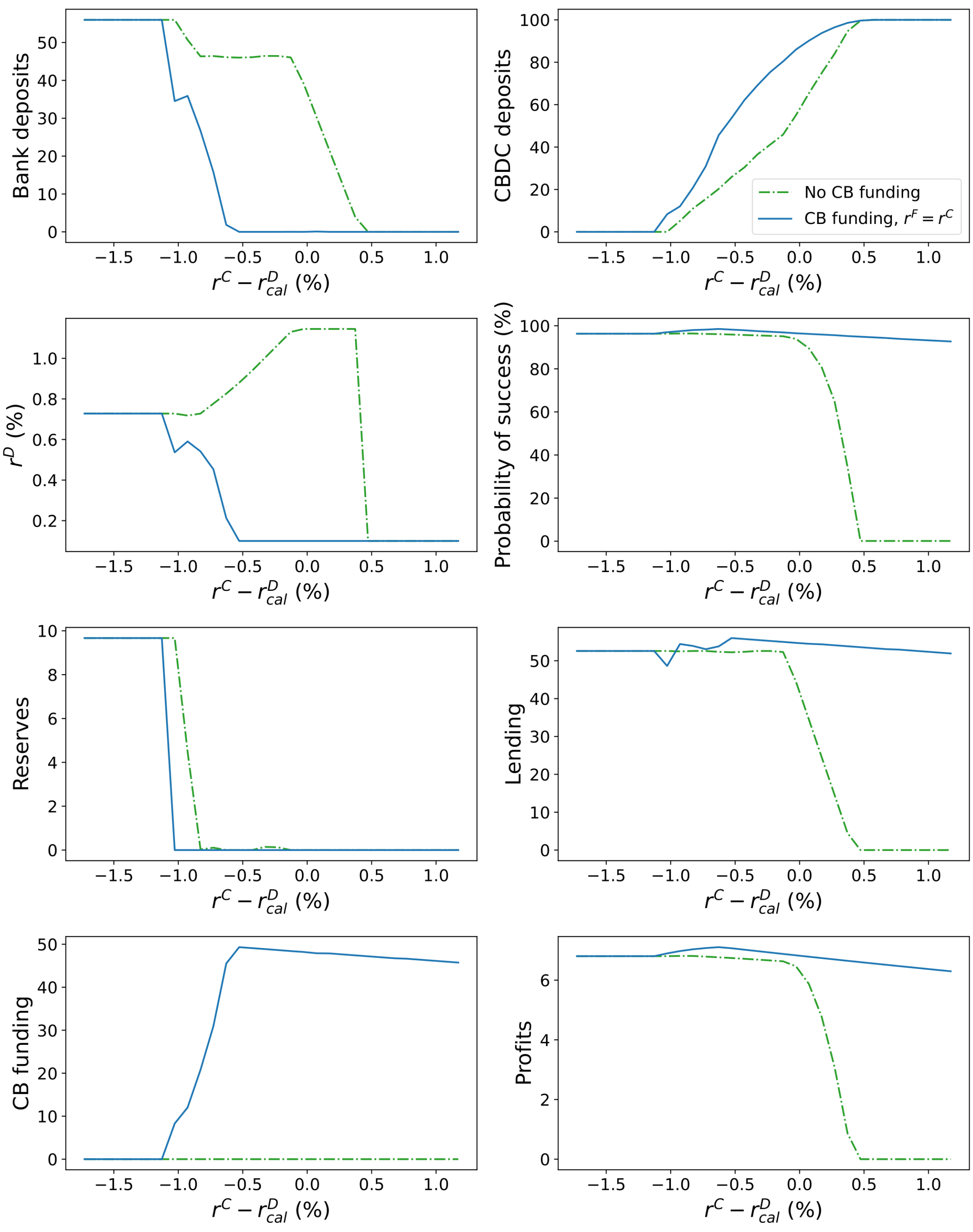

Figure 12. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C with the maximum CBDC convenience yield set to $\overline{\gamma} = 1$. The solid blue line represents the scenario where the commercial bank can borrow from the central bank at r^C. The dashed green line represents the scenario where the commercial bank cannot borrow from the central bank. The bank can borrow up to the amount of CBDC in circulation and less then the loss in deposits due to the introduction of a CBDC.

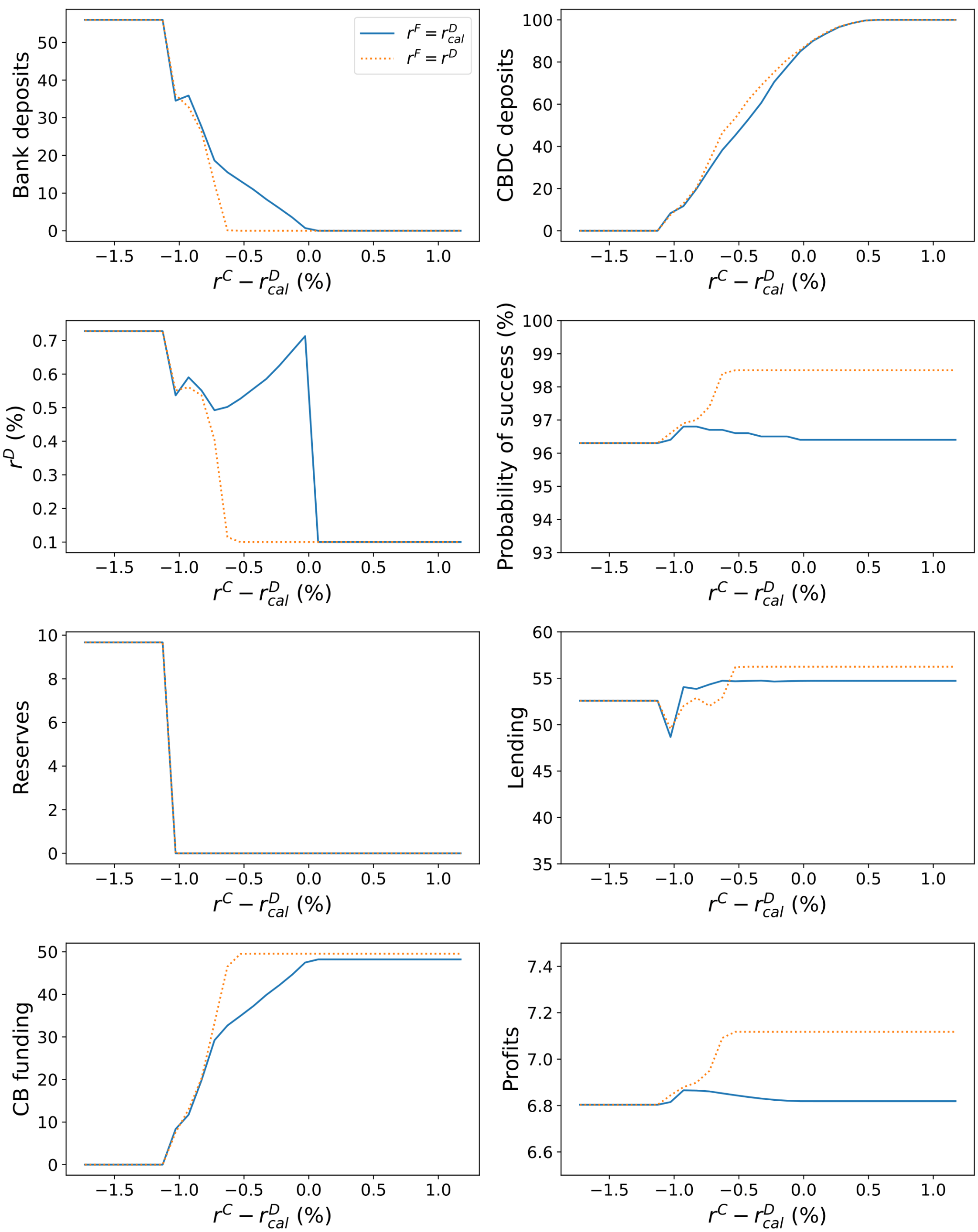

Figure 13. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C with the maximum CBDC convenience yield set to $\overline{\gamma} = 1$. The solid blue line represents the scenario where the commercial bank can borrow from the central bank at $r^D_c al$, the deposit rate in the equilibrium without a CBDC. The dotted orange line represents the scenario where the commercial bank can borrow from the central bank at r^D, the deposit interest rate set by the commercial bank. The bank can borrow up to the amount of CBDC in circulation and less then the loss in deposits due to the introduction of a CBDC.

C CBDC Convenience Yield Calibrated From Data

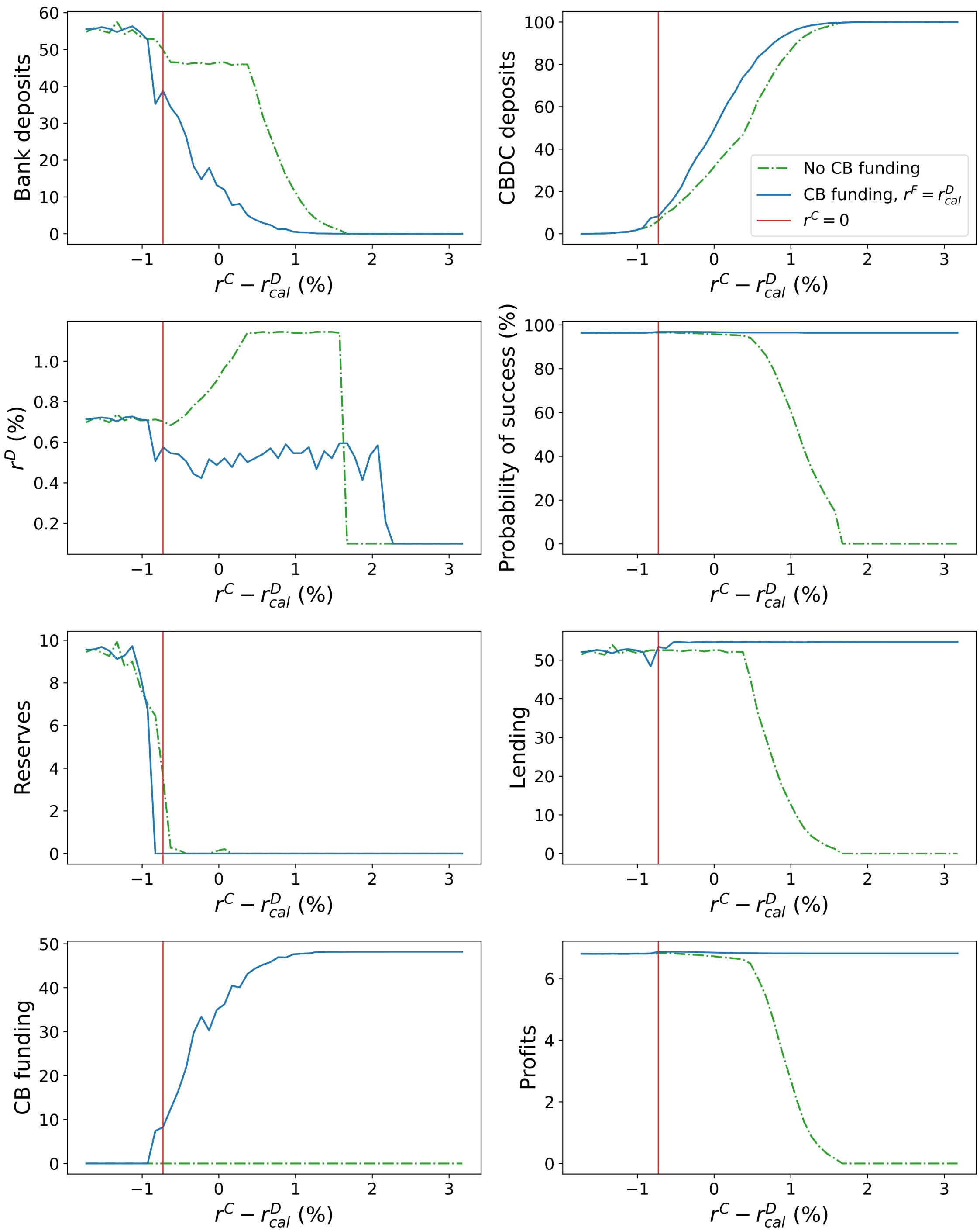

Figure 14. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C. The CBDC convenience yield distribution is calibrated using data from Bijlsma et al. (2021). The solid blue line represents the scenario where the commercial bank can borrow from the central bank at $r^F = r^D_{cal}$, which is the deposit rate in the equilibrium without a CBDC. The dashed green line represents the scenario where the commercial bank cannot borrow from the central bank. The bank can borrow up to the amount of CBDC in circulation and less then the loss in deposits due to the introduction of a CBDC. The vertical red line represents $r^C = 0$.

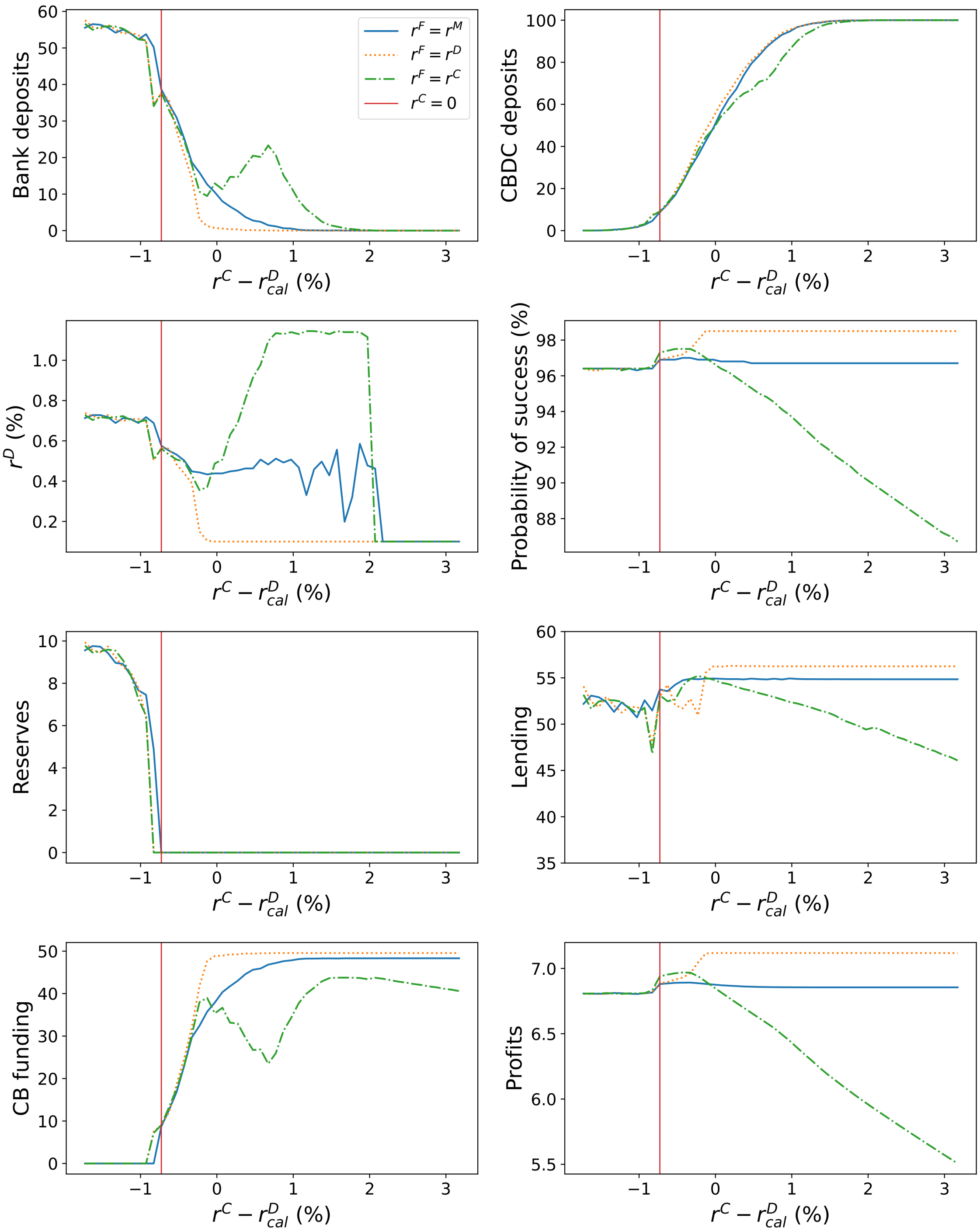

Figure 15. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C. The CBDC convenience yield distribution is calibrated using data from Bijlsma et al. (2021). The solid blue line represents the scenario where the commercial bank can borrow from the central bank at r^M, which is remuneration on central bank reserves. The dotted orange line represents the scenario where the commercial bank can borrow from the central bank at r^D, which is the deposit interest rate set by the commercial bank. The dashed green line represents the scenario where the commercial bank can borrow from the central bank at r^C. The bank can borrow up to the amount of CBDC in circulation and less then the loss in deposits due to the introduction of a CBDC. The vertical red line represents $r^C = 0$.