CBDC and Banks: Threat or Opportunity?

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ABSTRACT

A Central Bank Digital Currency (CBDC) would reduce commercial bank deposits and provide households with a new payment technology. We develop a structural model of the banking sector, calibrate it, and introduce a CBDC to run counterfactual analyses. We find that, if the central bank compensates the commercial banks for the loss in deposits, then banks optimally push households towards the CBDC. This allows them to capture the consumer surplus stemming from the new technology and increase their profit margin. The design of the compensation mechanism can mitigate this effect.

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] This definition does not distinguish between the two types of CBDC: the wholesale one, used for bank settlements, and the retail one, designed for the general public. While both might improve the current payment infrastructure, a retail CBDC could potentially change how the financial system works.[2] A recent survey by the Bank of International Settlements found that 80% of central banks are researching CBDCs and 40% of central banks have progressed from conceptual research to experiments, or proofs-of-concept (Boar, Holden, and Wadsworth, 2020). Most notably, the People's Bank of China is about to launch the first large-scale retail CBDC.[3] While policymakers are rushing towards digital money, there are still many open questions regarding the potential impact of such projects. Creating a digital version of physical cash would effectively give universal access to central bank liabilities, posing a challenge for the banking sector, creating new monetary policy tools, and changing the dynamics of the central bank balance sheet.

While other papers look at the general equilibrium effects of introducing a CBDC (see, e.g., Fernández-Villaverde, Sanches, Schilling, and Uhlig, 2020; Piazzesi, Rogers, and Schneider, 2022; Brunnermeier and Niepelt, 2019), we focus on the banking sector only, and assess the impact of different CBDC designs, with the help of a quantitative model. We address the following questions: Which CBDC design is the least disruptive for the banking sector? Will banks compete with the central bank for deposits? Could they capture the benefit stemming from the new technology?

Many central banks are considering the possibility of paying an interest rate on CBDC deposits (ECB, 2020). In this paper, we design the CBDC according to this working hypothesis, and we introduce and additional feature: the households' preference for the new technology. The technological benefit introduces an additional element, as households consider both the interest rate and the private benefit when making decisions on savings. A further important choice for policymakers, which is not related to the currency design, is whether to compensate the banking

[1] In this paper, we adopt the definition used by Kiff, Alwazir, Davidovic, Farias, Khan, Khiaonarong, Malaika, Monroe, Sugimoto, Tourpe, and Zhou (2020).

[2] In the rest of the paper CBDC indicates a retail CBDC. We do not discuss wholesale CBDC.

[3] Areddy, James, April 5th 2021, "China Creates Its Own Digital Currency, a First for Major Economy", The Wall Street Journal.

sector for the potential deposit drain. Various papers in the literature consider scenarios where households hold CBDC deposits and the central bank backs them with loans to the banking sector (see, e.g., Brunnermeier, James, and Landau, 2019; Niepelt, 2020). In our model, we allow banks to borrow money from the central bank when they do not have enough liquidity buffer to face the loss in deposits (central bank funding).

Our framework is a simplified version of the partial equilibrium dynamic model of the banking industry developed by Corbae and D'Erasmo (2021) and Corbae and D'Erasmo (2020). While our setting does not capture general equilibrium mechanisms, it allows us substantial flexibility in modeling the CBDC, and running counterfactual experiments with quantitative predictions. In the model, a representative bank accepts deposits from households and lends money to entrepreneurs. Entrepreneurs invest in risky projects and select the level of risk based on the interest rate set by the bank and the state of the economy, represented by an exogenous shock. The bank maximizes dividends by setting the interest rate on deposits and the one on loans. We calibrate the model on UK data and then introduce CBDCs with different designs to run counterfactual experiments. We obtain quantitative predictions of the bank's response to different levels of CBDC interest rates, households' technological preferences, and central bank funding.

In this context, we first introduce a CBDC that pays an interest rate, but with no possibility for the banking sector to borrow directly from the central bank. When there is no technological preference for CBDC, households only choose on the base yields, directly comparing interest rates on bank deposits and CBDC. Clearly, in this scenario, there are corner solutions. The CBDC is neutral (because it is not attractive) up to the point where the banking sector can no longer compete with the CBDC interest rate. Once the CBDC becomes attractive, households shift from bank deposits, leading to a narrow-banking equilibrium with banks only relying on equity as a source of funding.[4] When households have a technological preference for CBDC, we observe that the commercial bank increases its deposit interest rate to compete with the central bank, the total amount of savings increases, and lending is not affected. These results indicate that moderate CBDC interest rates can pressure the banking sector, with positive effects for households and no real effects on lending.

[4] In reality, banks would switch to wholesale funding, but we do not consider this market in our model for the sake of simplicity.

We then introduce the possibility for the commercial bank to borrow from the central bank up to the total amount of CBDC. We find that commercial banks do not compete and push households towards the CBDC to borrow from the central bank at a low interest rate. The reason is the household technological preference. For any given deposit rate, there is a lower CBDC rate that attracts the same number of households, because of the additional benefit stemming from the technological preference. When banks are allowed to borrow from the central bank at a low interest rate, they prefer to do so rather than having to pay a higher deposit interest rate to achieve the same amount of funding. In other words, they capture the benefit of technological innovation. We see this reflected in the bank's profitability. When we set the funding interest rate equal to the CBDC one, the effect on profitability fades away.

The choice of CBDC design largely depends on the policy objectives. The arguments in favour of a CBDC can be classified into two main groups. First is the need for a digital form of state-issued money, as physical banknotes are becoming obsolete (Auer, Cornelli, Frost, et al., 2020). In the words of Sweden's central bank (Armelius, Boel, Claussen, and Nessén, 2018), *if the marginalisation of cash continues, a digital krona, an e-krona, could ensure that the general public still has access to a state-guaranteed means of payment.* The second argument concerns the effectiveness of monetary policy. While a CBDC could strengthen existing tools, it could also open new (digital) channels by steering deposit interest rates, distributing helicopter money or, in extreme cases, granting loans to the private sector (Coeuré and Loh, 2018). This new toolkit might influence competition in the financial industry by changing the set of actors at play.

Policymakers have three main design choices to make (Allen, Capkun, Eyal, Fanti, Ford, Grimmelmann, Juels, Kostiainen, Meiklejohn, Miller, et al., 2020). The first is between token-based and account-based currencies, the second is between single-tier and two-tier distribution systems, and the third is between DLT technologies and traditional centralized systems. In this paper, we mostly focus on the first one, as it is the one with the most economic consequences. The other choices are also important, but they mostly affect efficiency, data access, and the possibility to offer complementary services. The distinction between token and account-based payment systems is the verification needed for a transaction to occur (Kahn and Roberds, 2009)). Token-based systems rely on the verification of the payment object, like coins, banknotes, and digital tokens. By contrast, account-based systems rely on the verification of the account holder's identity. A central bank could easily decide to pay an interest rate on an account-based CBDC, while it would be problematic to do so for a token-based CBDC, as it would inevitably affect the value of the token itself.[5] Another major difference is the possibility of offline payments and anonymity, as token-based systems can allow for a level of anonymity that is impossible for an account-based system (Lagarde, 2018).

In this context, our paper gives two main contributions to the literature. First, it provides numerous insights into the response of the banking sector to different CBDC designs and shows that a token-based CBDC with no interest rate would be the least disruptive design for the banking sector. Second, it is the first paper, to the best of our knowledge, to provide a quantitative analysis of the introduction of a CBDC.

The rest of the paper is organized as follows. Section 2 reviews the extant literature, Section 3 presents the model, Section 4 shows the calibration of the model, Section 5 designs the CBDC in our model, Section 6 presents the results of the counterfactual exercises, and Section 7 concludes.

2 Literature Review

Our paper belongs to the recent strand of literature that studies the potential impact of introducing of a CBDC. More specifically, we focus on the impact on the banking sector, thus contributing to the literature that looks at the interaction between monetary policy and banks.

From the technical side, our model speaks to the *structural banking* strand of corporate finance literature (see, e.g., De Nicolo, Gamba, and Lucchetta, 2014; Hugonnier and Morellec, 2017) and is a simplified version of the one proposed in Corbae and D'Erasmo (2020) and Corbae and D'Erasmo (2021). To the best of our knowledge, it is the first dynamic banking industry model used to assess the impact of CBDCs.

At the moment of writing, no central bank launched a large-scale CBDC project, and, consequently, there is no empirical paper in the extant literature. Nevertheless, there are various papers by academics and policymakers that outline the main challenges of introducing a CBDC and digital money in general. Brunnermeier et al. (2019) provide an interesting framework to think about

[5] Most CBDC pilot projects use hybrid systems, like the e-peso issued by Uruguay's central bank (Bergara and Ponce, 2018).

digital money and suggest that technology might radically change the role of money as we may see an unbundling of its separate roles, creating fiercer competition among specialized currencies. Regarding CBDCs, the BIS report by Auer and Böhme (2020) points to the three main design choices: account- vs. token-based system, one- or two-tier distribution, and whether to adopt a decentralized ledger technology. Other reports issued by central banks define the design problem in similar terms (Armelius, Guibourg, Johansson, and Schmalholz, 2020). While on the account vs. token system the debate is still far from settled, policymakers are forming a consensus for a two-tier distribution system (see, e.g., Bindseil, 2019, 2020). Concerning technology, it is still not clear whether DLT technologies are scalable enough to support large payment infrastructures but many consider them an essential pillar of the digitization of the monetary system (Klein, Gross, and Sandner, 2020).

Other authors discussed 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. 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. We contribute to this ongoing debate by rationalizing the main trade-offs in a theoretical setting and highlighting the possible response of the banking sector.

A few theoretical models have studied the impact of CBDCs on the interaction between the central bank and commercial banks. 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. In this setting, the central bank invests 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. They conclude that the central bank would arise as a deposit monopolist. Piazzesi et al. (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 microfounded general equilibrium model with money and banking. They show that when banks have no market power, issuing a CBDC would crowd out private banking. On the other hand, when banks have market power in the deposit market, a CBDC with the proper interest rate would encourage banks to pay higher interests or offer better services to keep their customers. Our paper contributes to this literature by focusing on the consequences on banks' leverage and financing.

Finally, the question about optimal CBDC design is very much open. Agur, Ari, and Dell'Ariccia (2022) develop a theoretical model where depositors can choose between cash, CBDC, and bank deposits according to their preferences over anonymity and security. They find that the optimal CBDC design trades off bank intermediation against the social value of maintaining diverse payment instruments. As we use a partial equilibrium industry model, we can not answer this question. Nevertheless, our paper provides important insights by showing the different impact on banks of different CBDC interest rates.

3 A Model of Banking

Before introducing and analyzing the effect of CBDC, we develop a baseline dynamic partial equilibrium model of the banking sector. The setting is based on **?**.

We consider a representative commercial bank that operates over infinite time. Each period the bank intermediates between a unit mass of ex-ante identical entrepreneurs and a unit mass of households. The entrepreneurs borrow one unit from the bank and invest it in a technology that generates a stochastic return in the next period. The return depends on the economic shock. Households are risk-neutral and sufficiently patient to exercise their saving options. At the beginning of the period, the commercial bank observes the state of the economy and chooses the interest rates on loans and deposits. Finally, the central bank regulates the commercial bank and conducts monetary policy.

Figure 1 outlines the baseline structure, representing the relations between entrepreneurs, households, commercial bank, and central bank.

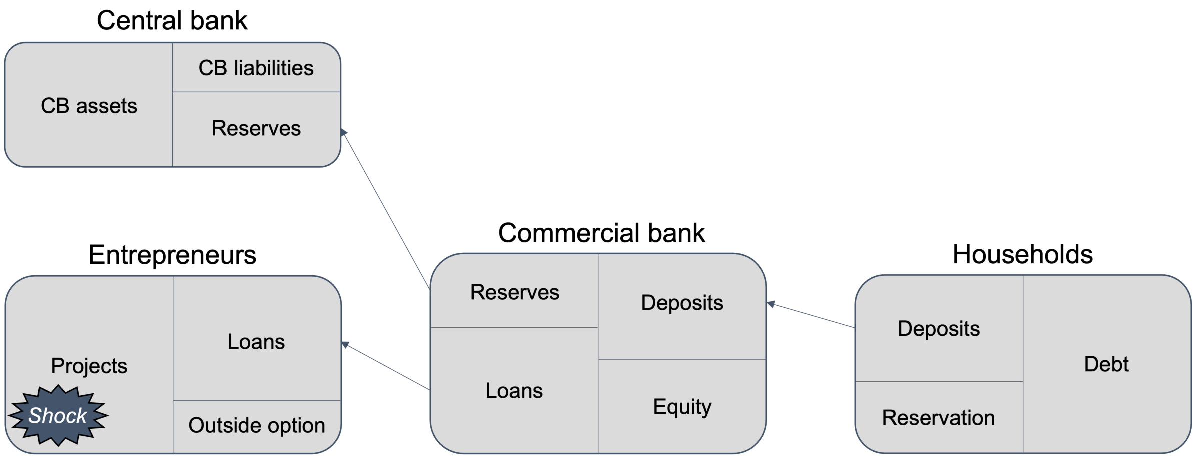

Figure 1. The figure illustrates the baseline model of the banking sector. The bank intermediates between entrepreneurs and households. Entrepreneurs borrow from the bank and invest in a technology generating a return that depends on the economic shock. Households put their savings in bank deposits. The bank decides the interest rates on loans and deposits. The central bank regulates the commercial bank and conducts monetary policy.

3.1 Entrepreneurs

The entrepreneurs are infinitely lived and risk-neutral. Each period, they need to borrow from the bank in order to fund a new project. The project requires one unit of investment and returns $\mathcal{R}$, which is stochastic and can assume the following values:

$$\mathcal{R}_t = \begin{cases} 1 + z_t R_{t-1}, & \text{with prob. } p(R_{t-1}, z_t) \\ 1 - \lambda, & \text{with prob. } 1 - p(R_{t-1}, z_t) \end{cases}, \tag{1}$$

where z_t is the aggregate shock realized in the current period, R_{t-1} the entrepreneurs' choice of technology in the previous period, $p(R_{t-1}, z_t)$ the probability of success, and λ the loss for project failure. The project's success is independent across entrepreneurs, but it depends on the entrepreneurs' choice of technology, $R_{t-1} \geqslant 0$, and the realized aggregate technology shock, z_t.

The aggregate shock represents the state of the economy and follows an log-AR(1) process:

$$\ln(z_t) = \rho \ln(z_{t-1}) + u_t, \tag{2}$$

where ρ is the autoregressive coefficient and u_t the innovation, that is i.i.d. and drawn from the normal distribution $\mathcal{N}(0, \sigma_u^2)$.

A project with higher returns has more risk of failure, and there is less failure in good times. We parametrize the stochastic process for the entrepreneurs' project as $s_t = az_t - bR_{t-1} + \varepsilon_t$, where ε_t is i.i.d. across agents and time and drawn from $\mathcal{N}(0, \sigma_\varepsilon^2)$. As the success is defined by $s_t > 0$, the probability of success is given by:

$$\begin{aligned} p(R_{t-1}, z_t) &= \Pr(s_t > 0 \mid R_{t-1}, z_t) \\ &= 1 - \Pr(s_t \leqslant 0 \mid R_{t-1}, z_t) \\ &= 1 - \Pr(\varepsilon_t \leqslant -az_t + bR_{t-1}) \\ &= \Phi\left(\frac{az_t - bR_{t-1}}{\sigma_\varepsilon}\right), \end{aligned} \tag{3}$$

where $\Phi(.)$ is a standard normal cumulative distribution. The technology exhibits a risk-return trade-off as the probability of success of the project is increasing with z_t and decreasing with R_{t-1}.

Entrepreneurs have an outside option (or reservation utility) $\omega_t \in [\underline{\omega}, \overline{\omega}]$, i.i.d. over time and drawn from distribution function $\Omega(\omega_t)$, that for simplicity we assume to be the uniform distribution $\mathcal{U}(\underline{\omega}, \overline{\omega})$. This outside option represents an alternative source of finance to the bank loan. While entrepreneurs are ex-ante identical, they are ex-post heterogeneous due to the shocks' realizations to the return on their project. Both R_{t-1} and ω_t are private information to the entrepreneur, as well as his history of past borrowing and repayments.

When the entrepreneur asks for a loan from the bank, there is a limited liability on the borrower's part. Therefore, the entrepreneur will pay back $1 + r^L$ in case of success, where r^L is the interest rate charged by the bank on the loan, and $1 - \lambda$ in the unsuccessful state. The expected payoff will be:

$$\begin{aligned} \Pi_t &= p\left(R_{t-1}, z_t\right)\left((1 + z_t R_{t-1}) - (1 + r_t^L)\right) + \left(1 - p(R_{t-1}, z_t)\right)\left((1 - \lambda) - (1 - \lambda)\right) \\ &= p\left(R_{t-1}, z_t\right)\left(z_t R_{t-1} - r_t^L\right). \end{aligned} \tag{4}$$

Entrepreneurs take the loan interest rate r^L as given and choose whether to demand a loan and, if so, the technology R. If they decide to participate and request a loan, the entrepreneurs choose the technology to solve the following problem:

$$v\left(r_t^L, z_{t-1}\right) = \max_{R_{t-1}} \ \mathbb{E}_{z_t|z_{t-1}}\left[\, p\left(R_{t-1}, z_t\right)\left(z_t R_{t-1} - r_t^L\right)\,\right] \tag{5}$$

$$\text{s.t.} \quad v\left(r_t^L, z_{t-1}\right) \geqslant \omega_t. \tag{6}$$

The first-order condition is given by:

$$\mathbb{E}_{z_t|z_{t-1}}\left[p\left(R_{t-1}, z_t\right) z_t + \frac{\partial p\left(R_{t-1}, z_t\right)}{\partial R_{t-1}}\left(z_t R_{t-1} - r_t^L\right)\right] = 0. \tag{7}$$

The first term is positive and represents the benefit of choosing a higher return project. The second term is negative and corresponds to the cost associated with the increased risk of failure. As the optimal choice of technology, R_{t-1}, depends on the loan interest rate r_t^L and the economic shock z_{t-1}, we can always express the project's probability of success as $p(r_t^L, z_{t-1}, z_t)$.

The aggregate demand for loans is:

$$L_t\left(r_t^L, z_{t-1}\right) = \int_{\underline{\omega}}^{\overline{\omega}} \mathbb{1}_{\omega_t \leqslant v\left(r_t^L, z_{t-1}\right)} d\Omega(\omega_t). \tag{8}$$

In other words, the total supply is the sum of all entrepreneurs for which the optimal project value is higher than the reservation value. Applying the envelope theorem, we can easily demonstrate that $\frac{\partial L_t\left(r_t^L, z_{t-1}\right)}{\partial r_t^L} < 0$, meaning that borrowers are worse off the higher the interest rate charged by the bank.

3.2 Households

Each period, risk-neutral households are endowed with one unit of good. They can choose to supply their endowment to a bank or an individual borrower. If households deposit their endowment with a bank, they receive an interest rate whether the bank succeeds or fails since we assume deposit insurance. Otherwise, if they directly fund the entrepreneurs' projects, then they must compete with bank loans. Hence, households could not expect to receive more than the bank lending rate r_t^L in successful states and must pay a monitoring cost. Since banks can minimize monitoring costs more efficiently, as in Diamond (1984), there is no benefit for households to fund entrepreneurs directly.

Households have also access to a storage technology that yields $1+\theta_t$, where the reservation value $\theta_t \in \left[\underline{\theta}, \overline{\theta}\right]$ is drawn from the distribution function $\Theta(\theta_t)$ and is i.i.d. over time. The reservation value θ_t is private information to the household. For simplicity, we assume $\Theta(\theta_t)$ to be a uniform distribution of type $\mathcal{U}\left(\underline{\theta}, \overline{\theta}\right)$. We can interpret the alternative saving option as a deposit outside the banking sector that pays θ_t, or as either cash or consumption with the reservation value as convenience yield.

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

$$D_t\left(r_t^D\right) = \int_{\underline{\theta}}^{\bar{\theta}} \mathbb{1}_{\theta_t \leqslant r_t^D} \, d\Theta(\theta_t). \tag{9}$$

We can easily prove that $\frac{\partial D_t(r_t^D)}{\partial r_t^D} > 0$, meaning that households are better off the higher the interest rate paid by the bank.

3.3 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 has to store at least δ of its deposits in reserves held at the central bank. Moreover, because of a possible moral hazard problem, 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 as liquidity buffer, and they are usually backed by safe assets (short-term government bonds).[6] After the global financial crisis in 2008, some 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

[6] For simplicity, at the moment we consider a partial equilibrium without modelling the market for government bonds. We will introduce government bonds in the model in a second moment to study the general equilibrium.

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.

Finally, the central bank sets the interest rate on reserves, using it as a monetary policy tool. For this reason, we assume that it depends on the economic shock, and we denote it with $r_t^M(z_{t-1})$.

3.4 Commercial Bank

The representative commercial bank intermediates between entrepreneurs, that need loans to fund their projects, and households, that hold their savings in the form of deposits. In its maximization problem, the bank chooses the interest rates on loans and deposits for the next period. These choices will determine the demand for loans and supply of deposits. At equilibrium, the demand and supply for loans and deposits meet because the respective markets clear.

Each period, 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. For each unit of lending, the commercial bank collect the agreed interest rate if the project succeeds, otherwise it looses λ. The expected payoff the loans is:

$$\mathcal{P}_t\left(r_t^L, z_{t-1}, z_t\right) = p\left(r_t^L, z_{t-1}, z_t\right)\left[1 + r_t^L\right] + \left[1 - p\left(r_t^L, z_{t-1}, z_t\right)\right][1 - \lambda]. \tag{10}$$

The total bank's profit is given by:

$$\pi_t\left(r_t^L, r_t^D, z_{t-1}, z_t\right) = \mathcal{P}_t\left(r_t^L, z_{t-1}, z_t\right) L_t\left(r_t^L, z_{t-1}\right) + \left[1 + r_t^M(z_{t-1})\right] M_t\left(r_t^D\right) - \left[1 + r_t^D\right] D_t\left(r_t^D\right), \tag{11}$$

where M_t is the amount of reserves held at the central bank, defined as a fraction δ of deposits:

$$M_t\left(r_t^D\right) = \delta D_t\left(r_t^D\right). \tag{12}$$

We define the dividends paid to the shareholders taking into account their limited liability:

$$d_{t+1}\left(r_t^L, r_{t+1}^L, r_t^D, r_{t+1}^D, z_{t-1}, z_t\right) = \max\left\{\pi_t\left(r_t^L, r_t^D, z_{t-1}, z_t\right); 0\right\} - f_{t+1}\left(r_{t+1}^L, r_{t+1}^D, z_t\right), \tag{13}$$

where f_{t+1} is the bank's equity. The equity is given by the following accounting identity:

$$f_{t+1}\left(r_{t+1}^{L}, r_{t+1}^{D}, z_t\right) = L_{t+1}\left(r_{t+1}^{L}, z_t\right) + M_{t+1}\left(r_{t+1}^{D}\right) - D_{t+1}\left(r_{t+1}^{D}\right), \tag{14}$$

with the constraint that $f_{t+1}\left(r_{t+1}^{L}, r_{t+1}^{D}, z_t\right) \geqslant \kappa\, L_{t+1}\left(r_{t+1}^{L}, z_t\right)$, where κ represents the capital requirement.

The bank's objective is to maximize the discounted stream of dividends paid to the shareholders. We denote with β the discount factor. The maximization problem can be written in the form of Bellman equation as follows:

$$V\left(r_t^{L}, r_t^{D}, z_{t-1}, z_t\right) = \max_{r_{t+1}^{L}, r_{t+1}^{D}} d_{t+1}\left(r_t^{L}, r_{t+1}^{L}, r_t^{D}, r_{t+1}^{D}, z_{t-1}, z_t\right) + \beta\, \mathbb{E}_{z_{t+1}|z_t}\left[V\left(r_{t+1}^{L}, r_{t+1}^{D}, z_t, z_{t+1}\right)\right], \tag{15}$$

where the aggregate shock z_{t+1} follows the log-AR(1) process in equation (2).

3.5 Timeline

We use x_t to indicate a variable that is observable at the beginning of period t and x_{t+1} for a variable that is observable at the end of the period.

The sequence of events in each period t of the model can be summarized as follows:

1. At the end of period $t-1$, the interest rates for loans and deposits, r_t^L and r_t^D, are public information. The entrepreneurs make their choice of technology R_{t-1}. Accordingly, L_t entrepreneurs demand and obtain a loan, and D_t households deposit their savings at the commercial bank.
2. At the beginning of period t, the aggregate shock z_t is realized.
3. Entrepreneurs make a profit or loss based on the previous period's choice of technology, and, accordingly, they repay the bank for the loan obtained in period $t-1$.
4. The bank gets the return from the previous period loans and reserves, and it pays back the interest on deposits. It makes the profit π_t.
5. The bank chooses the new interest rates on loans and deposits, r_{t+1}^L and r_{t+1}^D.
6. The reservation values for entrepreneurs and households, ω_{t+1} and θ_{t+1}, are drawn, and the new amount of loans and deposits, L_{t+1} and D_{t+1}, are determined.

7. At the end of the period, the bank pays the dividends d_{t+1} to the shareholders.

Table 5 and Table 5 in Appendix A summarizes the notation we use throughout the model.

4 Model Calibration

To bring our model to the data, we divide our identification strategy into two steps. The first step consists in directly calibrating a set of parameters. They are either pinned down from the data, arbitrary set to zero, or obtained from the extant financial literature. The second step consists in estimating the remaining parameters by matching specific moments.

Since the representative bank in our model portrays the entire banking sector, we use aggregate data for the UK banking sector. We distinguish two time periods with different monetary policies. The first interval goes from 1995 to 2007 to avoid considering the extraordinary monetary policy measures adopted during and after the financial crisis. The second period considers data from 2008 to 2020 to calibrate the baking sector subject to the quantitative easing policies adopted after the financial crisis.

We take the "Total Factor Productivity (TFP) at constant national prices for the United Kingdom" from FRED to calibrate the parameters associated with the stochastic process of aggregate technology shocks. We estimate the parameters ρ and σ_u in equation (2) by fitting the TFP series in a log-AR(1) process. With the values obtained, we simulate the aggregate shocks with a discretized log-AR(1) process using the method presented in Tauchen (1986). For tractability, we set the number of grid points to five (low, medium-low, medium, medium-high, high shocks).[7]

Financial regulators arbitrarily set the reserve and capital requirements. We measure the reserve ratio as the amount of reserves over the total amount of deposits in the UK. For the first period, we keep the capital requirement enforced by Basel I and Basel II (introduced in 2004), which requires banks to hold capital equal to at least 8% of their risk-weighted assets. Our model simplifies this concept as the ratio of equity over loans. For the second period, we use Basel III that brings the total minimum requirement to 7 percent.[8] Central banks also set the interest rate on reserves. For simplicity, we consider it as fixed (not depending on the economic shock) and we take the average

[7] Results are not substantially different if we increase the number of points in this grid.
[8] https://www.bis.org/bcbs/publications.htm?m=2566

annualized Bank Rate set by the Bank of England.

We measure the loss for project failure λ as the recovery rate on all loans for all commercial banks. We construct the series as the ratio between "charge-off rate on all loans, all commercial banks" and "delinquency rate on all loans, all commercial banks".[9] Finally, following Corbae and D'Erasmo (2021), we set the discount rate at 5%, and we establish the minimum household reservation value and the minimum entrepreneur outside option at zero by default. Table 1 reports the values for these parameters.

Table 1

The table shows the values of the model parameters that we either pin down from the data, arbitrary set to zero, or obtain from the extant financial literature.

Par.	Definition	Value 1995-2008	Value 2009-2020	Source
β	Discount factor	0.95	0.95	(default)
δ	Reserve ratio	0.029	0.244	Bank of England
κ	Capital requirement	0.08	0.07	Basel
λ	Loss for project failure	0.302	0.276	Bank of England
ρ	Aggregate shock persistence	0.844	0.614	FRED
σ_u	Aggregate shock distribution (%)	0.718	0.874	FRED
r^M	Average bank rate (annualized)	0.053	0.008	Bank of England
$\underline{\omega}$	Min entrepreneur outside option	0	0	(default)
$\underline{\theta}$	Min household reservation value	0	0	(default)

The remaining parameters cannot be pinned down from the data. Therefore we estimate them by matching specific moments that we can observe. Table 2 summarizes the identification strategy.

Table 2

The table shows the values of the model parameters that we calibrate targeting specific moments.

Par.	Definition	Value 1995-2008	Value 2009-2020	Target moment
σ_ε	Project success distribution	0.090	0.170	ROE
a	Success prob., weight shock	2.600	4.300	Default frequency
b	Success prob., weight risk	26.000	25.600	Borrower return
$\overline{\omega}$	Max entrepreneur outside option	0.315	0.295	Interest margin
$\overline{\theta}$	Max household reservation value	0.022	0.046	Leverage

We estimate the success volatility of the projects, σ_ε, by targeting the return on equity (ROE).

[9] The data used for this estimate are from the US. We make the strong assumption that they are somehow similar in the UK.

The project's probability of success is inversely correlated to volatility, meaning that entrepreneurs can take up riskier projects and afford higher interest rates for low levels of volatility. In turn, higher interest rates translate into higher ROE for the bank.

We look at the loans' default frequency to calibrate a, the weight of the aggregate shock in the project's probability of success. When this weight increases, so does the probability of success of the entrepreneurs' projects. Thanks to this, the default frequency is lower for higher values of a.

The other parameter in the project's probability of success, b, is the weight of the entrepreneur's choice of project risk. We target the borrower return, that we proxy with the S&P500 annual return. The intuition is that, for higher b, entrepreneurs' probability of success of their projects decreases, leading to lower returns.

The maximum entrepreneur reservation value, $\overline{\omega}$, determines the demand for loans, given the interest rate and the shock on the economy. If entrepreneurs have a valid outside option, they reduce the demand for loans. With less loans, the bank needs less funding, thus offering a lower interest rate on deposits and increasing its intermediation margin.

Finally, we calibrate the maximum household reservation value $\overline{\theta}$ by matching the leverage, defined as equity over total assets. Increasing the maximum reservation value of households makes deposits more expensive for the bank, thus forcing it to increase interest rates on loans. In response, entrepreneurs choose riskier projects, making the overall bank riskier and increasing moral hazard. Therefore the bank chooses higher leverage to benefit more from limited liability and government bailouts.

Table 3

The table shows the targeted moments obtained from the data and the model estimate.

Moment	Target (%) 1995-2008	Estimate (%) 1995-2008	Target (%) 2009-2020	Estimate (%) 2009-2020
ROE	14.81	15.84	2.72	3.41
Default frequency	2.23	2.02	2.33	2.38
Borrower return	7.94	7.08	10.02	11.75
Interest rate margin	1.61	1.53	1.58	1.27
Leverage	9.17	8.92	9.32	9.19

Table 3 displays the values obtained from the data (target) and the ones from the calibration of our model (estimate). The parameters generate moments that are relatively close to the ones from the data. We report the main moments of the banking sector at equilibrium in Table 4.

Table 4
The table shows the main moments of the banking sector obtained from the model calibration.

Moment	Estimate (%) 1995-2008	Estimate (%) 2009-2020
Deposit interest rate	0.5	2.1
Lending interest rate	2.0	3.4
Bank deposits	23.1	46.5
Lending	22.5	39.8
Profits	2.6	0.8
Equity	2.6	4.7
Leverage	9.2	9.2
ROE	15.8	3.4
Dividends	0.3	0.2

5 Counterfactual: CBDC

We introduce a CBDC in the baseline model calibrated in Section 4. We model the CBDC as a direct liability of the central bank as shown in Figure 2.

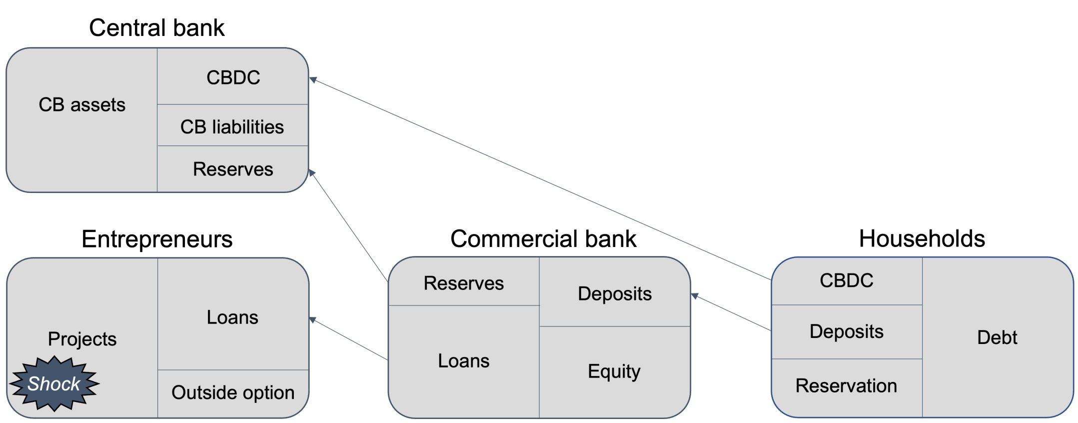

Figure 2. The figure illustrates the model of the banking sector with a CBDC. The bank intermediates between entrepreneurs and households. Entrepreneurs borrow one unit from the bank and invest it in a technology. The entrepreneurs' projects generate returns that depend on the economic shock. Households put their savings in bank deposits or CBDC. If the commercial bank does not have enough liquidity buffer to accommodate the demand for CBDC, it can borrow additional funds directly from the central bank. The central bank exogenously sets the interest rate on CBDC. The bank decides the interest rates on loans and deposits.

In line with current working hypotheses,[10] we assume that a CBDC can pay an interest rate. For

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

simplicity, we assume that the central bank exogenously sets a fixed interest rate r^C. Alternatively, the central bank could use the CBDC interest rate as a new monetary policy tool, observing the state of the economy and choosing the CBDC rate for the next period: $r_t^C\left(z_{t-1}\right)$.

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. The reasons could be multiple. Firstly, a CBDC would introduce an element of technological innovation with features like money programmability, instantaneous settlement, smart contracts, and decentralized financial services. Secondly, as a CBDC is issued by the central bank, it could provide a safe and trustworthy instrument to citizens. Lastly, 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, households have a heterogeneous preference for CBDC. The preference of each household, γ_t, is drawn every period from the distribution function $\Gamma\left(\gamma_t\right)$, that we assume i.i.d. over time and uniform $\mathcal{U}\left(\underline{\gamma},\overline{\gamma}\right)$. We also assume that nobody has a negative preference for technology, and thus we set $\underline{\gamma}=0$ because a CBDC would add new possibilities without precluding current ones.

For the sake of simplicity, we assume that the preference for technology can be expressed as an extra yield, to be added on top of r^C, and compared against compared against the interest rate on deposits r_t^D and the reservation value θ_t. The reservation value is randomly drawn each period and independent of the preference. The bank deposit supply is the following:

$$\tilde{D}_t\left(r_t^D\right)=\int_{\underline{\gamma}}^{\overline{\gamma}}\int_{\underline{\theta}}^{\overline{\theta}}\mathbb{1}_{\{r^C+\gamma_t\leqslant r_t^D\}}\mathbb{1}_{\{\theta_t\leqslant r_t^D\}}\,d\Theta(\theta_t)d\Gamma(\gamma_t),\tag{16}$$

while the CBDC supply is:

$$C_t\left(r_t^D\right)=\int_{\underline{\gamma}}^{\overline{\gamma}}\int_{\underline{\theta}}^{\overline{\theta}}\mathbb{1}_{\{r^C+\gamma_t>r_t^D\}}\mathbb{1}_{\{r^C+\gamma_t>\theta_t\}}\,d\Theta(\theta_t)d\Gamma(\gamma_t).\tag{17}$$

5.1 CBDC Introduction Mechanism

Since financial institutions are the only ones that can create money by lending, we assume that all the savings pass through the commercial bank in the first place. After resources are allocated, the commercial bank accommodates the demand for CBDC by transferring households' savings to the central bank. The amount of money that households want to transfer from bank deposit to CBDC is:

$$\tau_t\left(r_t^D\right) = D_t\left(r_t^D\right) - \tilde{D}_t\left(r_t^D\right), \tag{18}$$

where the first term of the equation is the demand for deposit in the baseline model without CBDC, as in equation (9), and the second term is the demand for deposit that remains at the bank, considering the interest rate, the reservation value, and the preference for CBDC as in equation (16).

Following Fraschini, Somoza, and Terracciano (2021), the commercial bank accommodate the demand for CBDC by optimally reducing its reserves whenever it is possible, that means whenever there are excess reserves. In other words, the commercial bank uses its liquidity buffer to compensate for the sudden loss of funds in terms of deposits. On the other hand, the central bank swaps one type of liability (reserves) into another (CBDC). As the liquidity requirement remains valid, the transfer affects the bank reserves in the following way:

$$M_t\left(r_t^D\right) = \max\left\{\delta D_t\left(r_t^D\right) - \tau_t\left(r_t^D\right); \phi\right\}, \tag{19}$$

where ϕ is the threshold after which the commercial bank does not want to switch reserves into CBDC anymore. The commercial bank might want a bigger liquidity buffer than the liquidity requirement for different reasons, and ϕ represents this need. For simplicity, we set $\phi = 0$.[11]

If the demand for CBDC is higher than the amount of reserves that can be swapped, that means $\tau_t > \delta D_t\left(r_t^D\right) - \phi$, then the commercial bank can ask for direct funding from the central bank. This scenario, where the central bank channels CBDC deposits back to banks, is often considered as the baseline in the literature (see e.g., Brunnermeier et al., 2019; Niepelt, 2020), even if its conditions are not extensively discussed in the central banks' reports. Here, we limit this possibility to the extreme case where the commercial bank does not have enough liquidity to deal with the loss of funds. Therefore, the amount of central bank's funding to the bank is:

$$F_t\left(r_t^D\right) = \max\left\{0; \tau_t\left(r_t^D\right) - \delta D_t\left(r_t^D\right) + \phi\right\}. \tag{20}$$

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

The central bank could ask an interest rate r_t^F on the direct funding. This interest rate could either match the interest rate on reserves, on CBDC or on deposits, or it could be used as an additional monetary policy tool.

The equation for the bank's profit changes to account for the possibility of this new type of liability on the commercial bank's balance sheet:

$$\pi_t\left(r_t^L, r_t^D, z_{t-1}, z_t\right) = \mathcal{P}_t\left(r_t^L, z_{t-1}, z_t\right) L_t\left(r_t^L, z_{t-1}\right) + \left[1 + r_t^M(z_{t-1})\right] M_t\left(r_t^D\right) \\ - \left[1 + r_t^D\right] \tilde{D}_t\left(r_t^D\right) - \left[1 + r_t^F\right] F_t\left(r_t^D\right). \quad (21)$$

The same happens to the equity:

$$f_{t+1}\left(r_t^L, r_{t+1}^L, r_t^D, r_{t+1}^D, z_{t-1}, z_t\right) = L_{t+1}\left(r_{t+1}^L, z_t\right) + M_{t+1}\left(r_{t+1}^D\right) - \tilde{D}_{t+1}\left(r_{t+1}^D\right) - F_{t+1}\left(r_{t+1}^D\right). \quad (22)$$

Finally, the equation for dividends and the maximization problem remain the same.

6 CBDC Effects

The effects of introducing a CBDC in the economy come from three different design features: the households' preference for technology, the CBDC interest rate, and whether we allow or not the central bank to compensate the commercial bank for the loss in deposits.

In this Section, we study these effects by simulating the calibrated model with the CBDC counterfactual. In other words, we keep the same parameter estimates obtained in the calibration in Section 4, we introduce a CBDC in the model as in Section 5, and we simulate the commercial bank's response.

6.1 Preference Effects

The representative commercial bank chooses the optimal interest rate on deposits considering the CBDC interest rate exogenously set by the central bank. However, for any given r_t^D, the total amount of savings (in terms of bank deposits and CBDC) is higher when households have access to a CBDC. The reason is that there can be households for which r_t^D is lower than their reservation value, but their technological preference is so high that they choose the CBDC rather than the alternative saving option. Figure 3 shows this mechanism by representing the distribution of households' total assets. In the model, this increase in the amount of savings in the "regulated" banking sector (bank deposits and CBDC), and it could represent the financial inclusion that some central banks are seeking with the introduction of a CBDC.

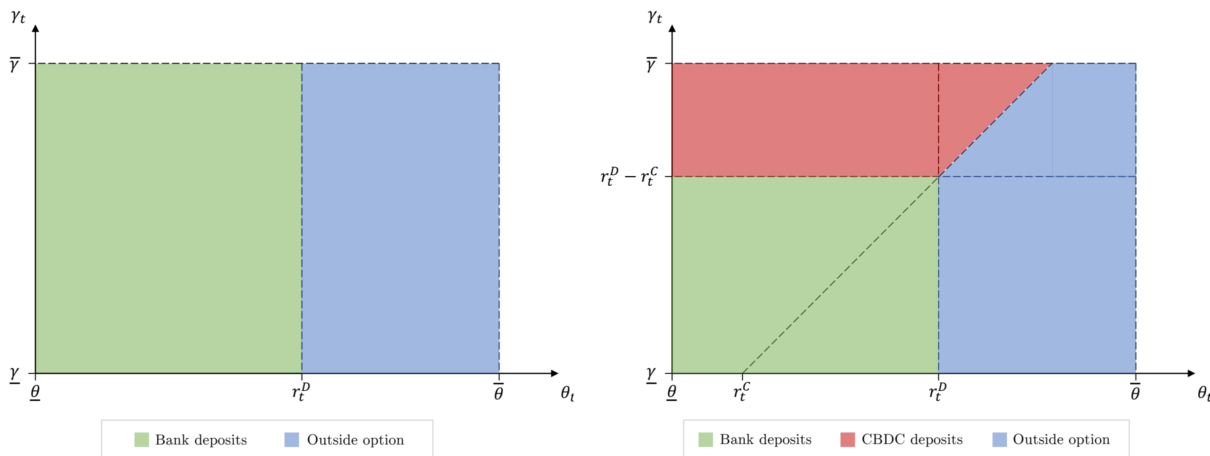

Figure 3. The figure shows the distribution of households' preferences along two dimensions: reservation value and preference for technology.

As we do not have any data to pin down the maximum households' preference for technology $\bar{\gamma}$, we consider different values: $\bar{\gamma} \in \left[0, \bar{\theta}\right]$, where $\bar{\theta}$ is the maximum households' reservation value. This choice allows the households always to have an alternative option for their savings. We consider three levels of maximum technological preference: null, intermediate, and high. When $\bar{\gamma} = 0$, it means that households have no technological preference, and their choice is based solely on the interest rates on deposits and CBDC. Since the technological preference is uniformly distributed, raising the maximum value of the interval increases the average technological preference. With a high level of technological preference, the maximum preference for technology is equal to the maximum households' reservation value ($\bar{\gamma} = \bar{\theta}$). Since in Section 4 we calibrated the maximum households' reservation value to 2.2% (or 4.6% under QE), in the high technological preference scenario the average household is willing to forgo an interest rate of 1.1% (or 2.3% under QE) in exchange for a superior payment technology.

6.2 CBDC Interest Rate Effects

In our simulations, the CBDC pays a fixed interest rate r^C in each state of the economy. We show the key moments of the banking sector varying with different values of the CBDC interest rate, that we set exogenously. Each point on the r^C grid corresponds to a different optimization of the representative commercial bank and respective simulation results. We also show how the different levels of technological preference (none, medium, high) change the results.

Figure 4 shows the main moments obtained from the simulations under quantitative easing policy. The solid blue line represents the effects of introducing a CBDC in absence of technological preference, the dotted orange line the ones with a medium preference, and the dashed green line the ones with a high preference.

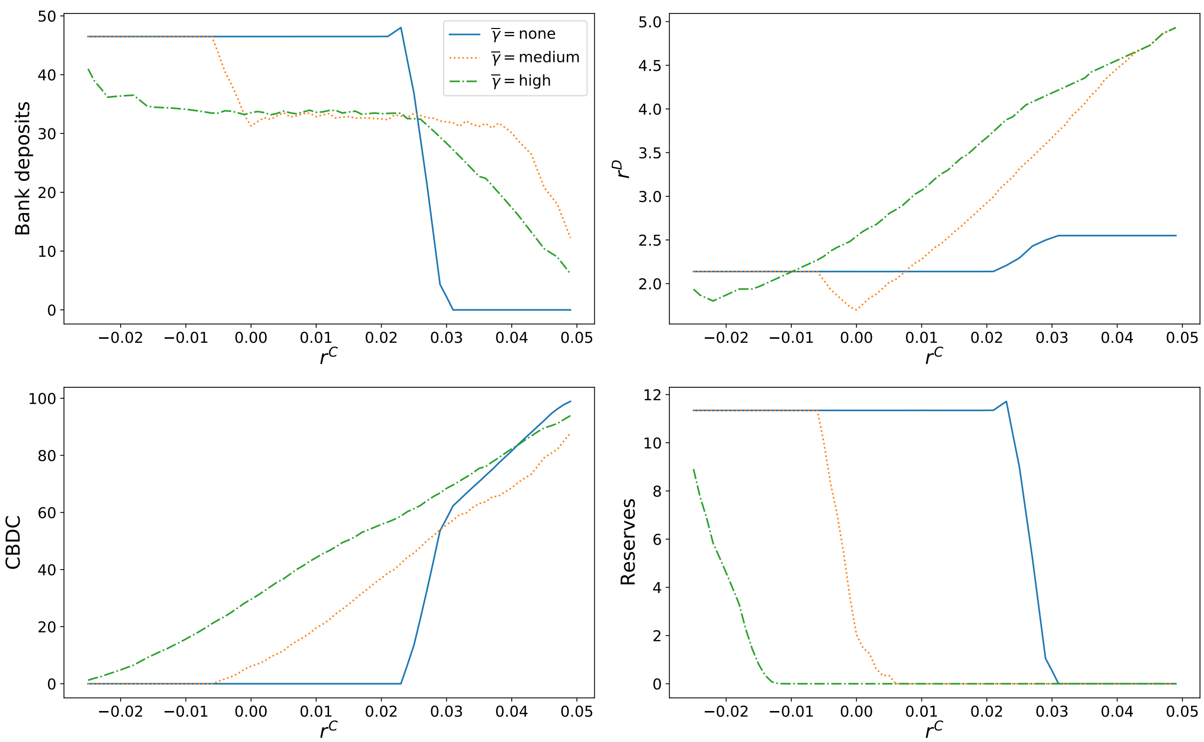

Figure 4. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C and the maximum households' technological preference $\bar{\gamma}$. It focuses on the amount of bank deposits, CBDC, and reserves, and on the interest rate on deposits.

Without any technological preference (solid blue line), there are only corner solutions. In the first equilibrium, the CBDC is not attractive enough and households keep holding their savings in the form of bank deposits. This is the same equilibrium as in the baseline scenario without a CBDC. The commercial bank does not gather all the households' savings because they have a heterogeneous reservation value. The second equilibrium sees a sudden switch of households' savings from bank deposits to CBDC. The higher the CBDC interest rate, the higher the amount of households that prefer holding CBDC (even to the alternative saving option). This equilibrium, however, is not feasible for the commercial bank, as it should finance itself only through equity (narrow-banking) or cease operations. In reality, banks would switch to wholesale funding that we do not consider in our model for the sake of simplicity.

If households have a heterogeneous technological preference, there are no corner solutions. In these scenarios (dotted orange and dashed green lines), the commercial bank competes with the central bank to retain deposits. As we can notice in Figure 4, the commercial bank increases the interest rate on deposits to make them more attractive to households. With higher technological preference, the competition starts for lower CBDC interest rates. The reason is that the commercial bank needs to compensate for the stronger CBDC preference with higher interest rates on deposits.

We also notice that the commercial bank prefers to get rid of reserves before starting to compete on interest rates. This result is in line with the theoretical prediction in Fraschini et al. (2021). However, this behaviour is possible only if there are excess reserves or, in other words, only under quantitative easing policy. Under standard policy, we expect the competition to start for lower CBDC interest rates as the commercial bank does not have any liquidity buffer.

Figure 7 in Appendix B exhibits all the key moments in the banking sector, obtained with the same simulations.

6.3 Central Bank Funding Effects

We know allows the central bank to compensate the commercial bank for the loss in deposits when there is no liquidity buffer. As mentioned in Section 5, the central bank could ask an interest rate r_t^F on the direct funding. For the moment, we set this interest rate to match the interest rate on reserves (Bank Rate): $r^F = r^M$. We explore different choices later in the Section. Finally, for better clarity, we present results only for a medium technological preference.[12].

Figure 5 shows the main moments obtained from the simulations in which we allow the central bank to fund the commercial bank (solid blue line) and compares them with the scenario without

[12]Results for other levels of technological preference can be found in Appendix B

central bank funding (dotted orange line). It is worth noting that the dotted orange line is the same as in Figure 4.

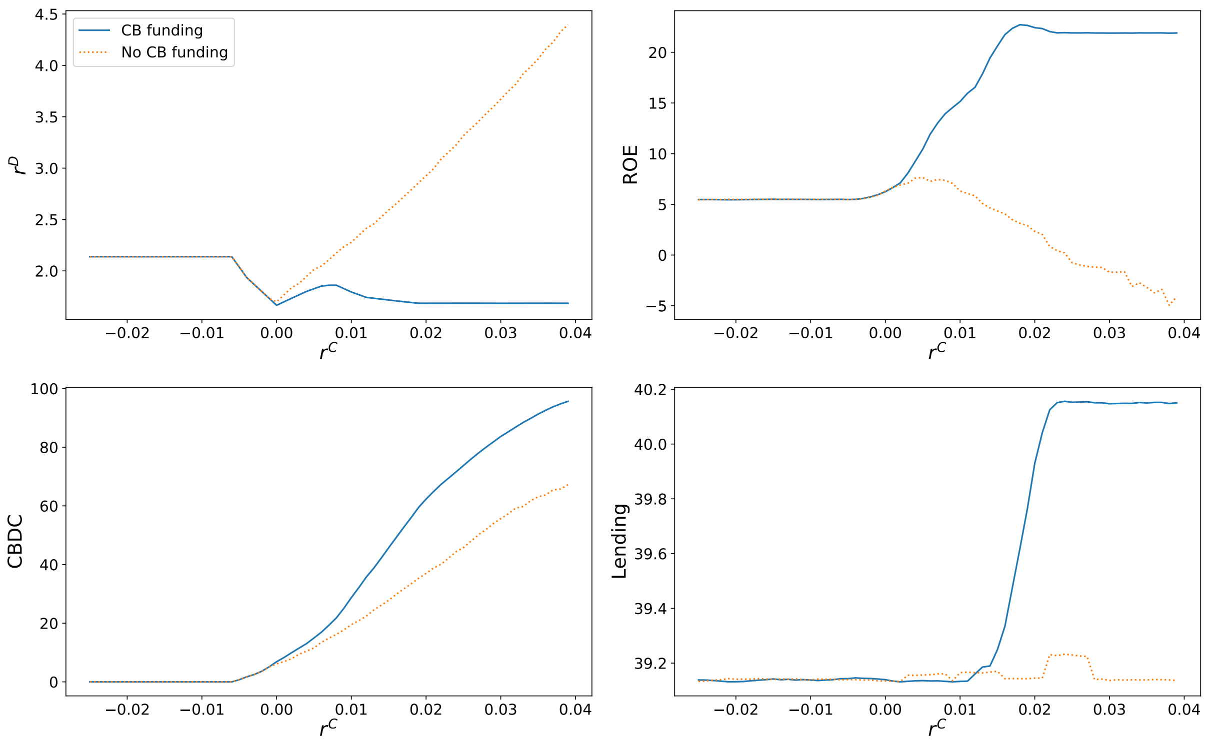

Figure 5. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C and the maximum households' technological preference $\bar{\gamma}$ set to a medium level. It focuses on the deposit interest rate, the amount of CBDC and lending, and the ROE of the commercial bank. It compares the scenarios in which we allow or not the central bank to compensate the commercial bank for the loss in deposits.

When the commercial bank has the possibility to borrow funds from the central bank, it never competes on interest rates to retain deposits. On the contrary, the commercial bank opportunistically takes advantage of the households' technological preference. In fact, it reduces the interest rate on deposits, pushing households towards the CBDC, and it never increases it. Since households have a private benefit from the technology, the commercial bank tries to make the CBDC even more attractive. We can clearly see this behaviour in Figure 6, where deposit interest rates remain low even for high CBDC interest rates and the amount of CBDC is higher than in the scenarios without central bank funding. The reason why the commercial bank chooses to not compete is that, by pushing households towards the CBDC, it can borrow cheaper funds from the central banks.

When we allow for direct central bank funding, the commercial bank seizes the opportunity and benefits from the households' technological preference, by pushing them towards a CBDC and borrowing at a cheaper interest rate from the central bank. Thanks to its opportunistic behaviour, the commercial bank increases its lending and ROE. In other words, the commercial bank is able to capture the benefit of technological innovation.

Figure 8 in Appendix B exhibits all the key moments in the banking sector, obtained with the same simulations.

Figure 6 shows the main moments obtained from the simulations in which we allow the central bank to fund the commercial bank. The central bank can ask for different interest rates on the funding: the reserve one (solid blue line), the deposit one (dotted orange line), and the CBDC one (dashed green line). It is worth noting that the solid blue line is the same as in Figure 5.

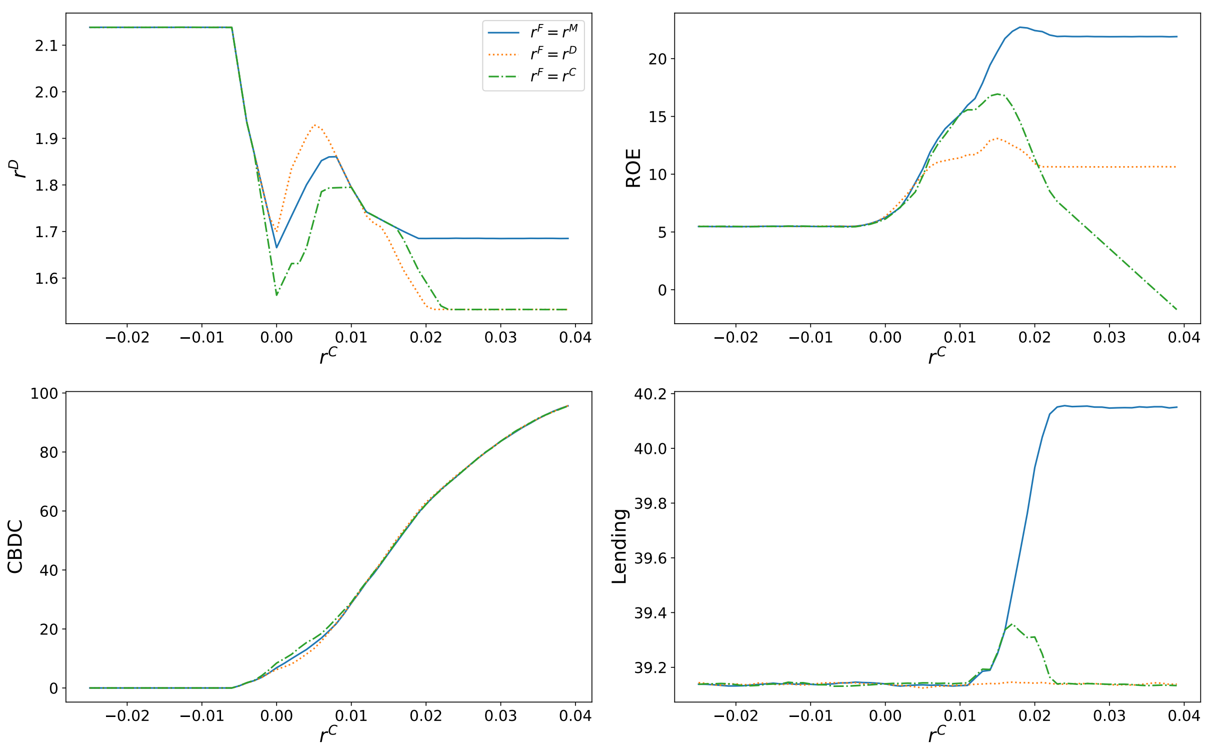

Figure 6. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C and the maximum households' technological preference $\bar{\gamma}$ set to a medium level. It focuses on the deposit interest rate, the amount of CBDC and lending, and the ROE of the commercial bank. It compares the scenarios in which we allow the central bank to compensate the commercial bank for the loss in deposits with different funding interest rates.

The behaviour of the commercial bank does not seem to dramatically change with different policies for the central bank funding interest rate. In each scenario, the bank chooses not to compete to retain deposits and push households towards a CBDC.

The main difference is the ROE. When the funding interest rate is set to match the deposit interest rate, the commercial bank achieves a lower ROE than when the interest rate matches the reserve one. This happens because the equilibrium interest rate on deposits (that the commercial bank decides with the maximization problem) is higher than the one on reserves (historically low). Clearly, the ROE decreases for higher CBDC interest rates when the central bank sets the funding interest rate equal to the CBDC one. As funding becomes more and more expensive, the commercial bank loses profits which lead to a lower ROE.

Figure 9 in Appendix B exhibits all the key moments in the banking sector, obtained with the same simulations.

7 Conclusions

In this paper, we develop a structural model of the banking industry to analyze its reaction when introducing a CBDC. In our setting, the CBDC provides a private technological benefit to households, and it can be interest-bearing. We consider two main scenarios.

In the first one, the commercial bank can only compete with the central bank for deposits by raising the deposit interest rate. We find that with a high private benefit from the CBDC, the bank would have to increase deposit rates to secure funding even if the CBDC pays no interest. For high CBDC interest rates, the bank stops competing altogether and ceases operations.

In the second scenario, we allow the commercial bank to borrow from the central bank up to the total amount held by households in CBDC. In this setting, the bank is able to capture part of the private benefits from the CBDC technology by offering lower deposit rates and pushing depositors with a high technological preference toward the CBDC. Thanks to this, the commercial bank can borrow funds at a lower interest rate. The result is an increase in profitability in terms of ROE.

These results have important policy implications. When introducing a CBDC, the central bank should be careful about how the benefits stemming from the new technology are distributed among the various agents. Paying a CBDC interest rate higher or similar to the deposit rate would severely affect bank lending. Allowing banks to borrow at low interest rates would transfer the technological benefits from households to the banking sector.

A possible solution would be not to pay any interest on the CBDC while charging banks the deposit interest rate on central bank funding. This design would be neutral for the banking sector while preventing it from capturing the technological benefit. The central bank would collect a sizable seignorage revenue that could be transferred back to households by the government.

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A Model Notation

Table 5

This table summarizes the notation for the variables used throughout the model.

Variable	Definition
r^L	Loan interest rate
r^D	Bank deposit interest rate
r^M	Reserve interest rate
r^C	CBDC deposit interest rate
L	Loans
D	Bank deposits
M	Reserves
C	CBDC deposits
π	Bank's profit
f	Bank's equity
d	Dividends
z	Aggregate shock
u	Aggregate shock innovation
$\mathcal{R}$	Project stochastic return
s	Project success
ε	Project success innovation
p	Project's probability of success
R	Entrepreneur's choice of technology
Π	Entrepreneur's payoff
$\mathcal{P}$	Project expected payoff to bank
v	Optimal project value
ω	Entrepreneur's outside option
θ	Household's reservation value
γ	Household's preference for CBDC

Table 6

This table summarizes the notation for the parameters used throughout the model.

Parameter	Definition
β	Discount factor
δ	Liquidity requirement
κ	Capital requirement
λ	Loss for project failure
ρ	Aggregate shock persistance
σ_u	Aggregate shock distribution
a	Success probability, weight shock
b	Success probability, weight risk
σ_ε	Project success distribution
$\underline{\omega}$	Min entrepreneur outside option
$\overline{\omega}$	Max entrepreneur outside option
$\underline{\theta}$	Min household reservation value
$\overline{\theta}$	Max household reservation value
$\underline{\gamma}$	Min household preference for CBDC
$\overline{\gamma}$	Max household preference for CBDC

B Figures for CBDC Effects

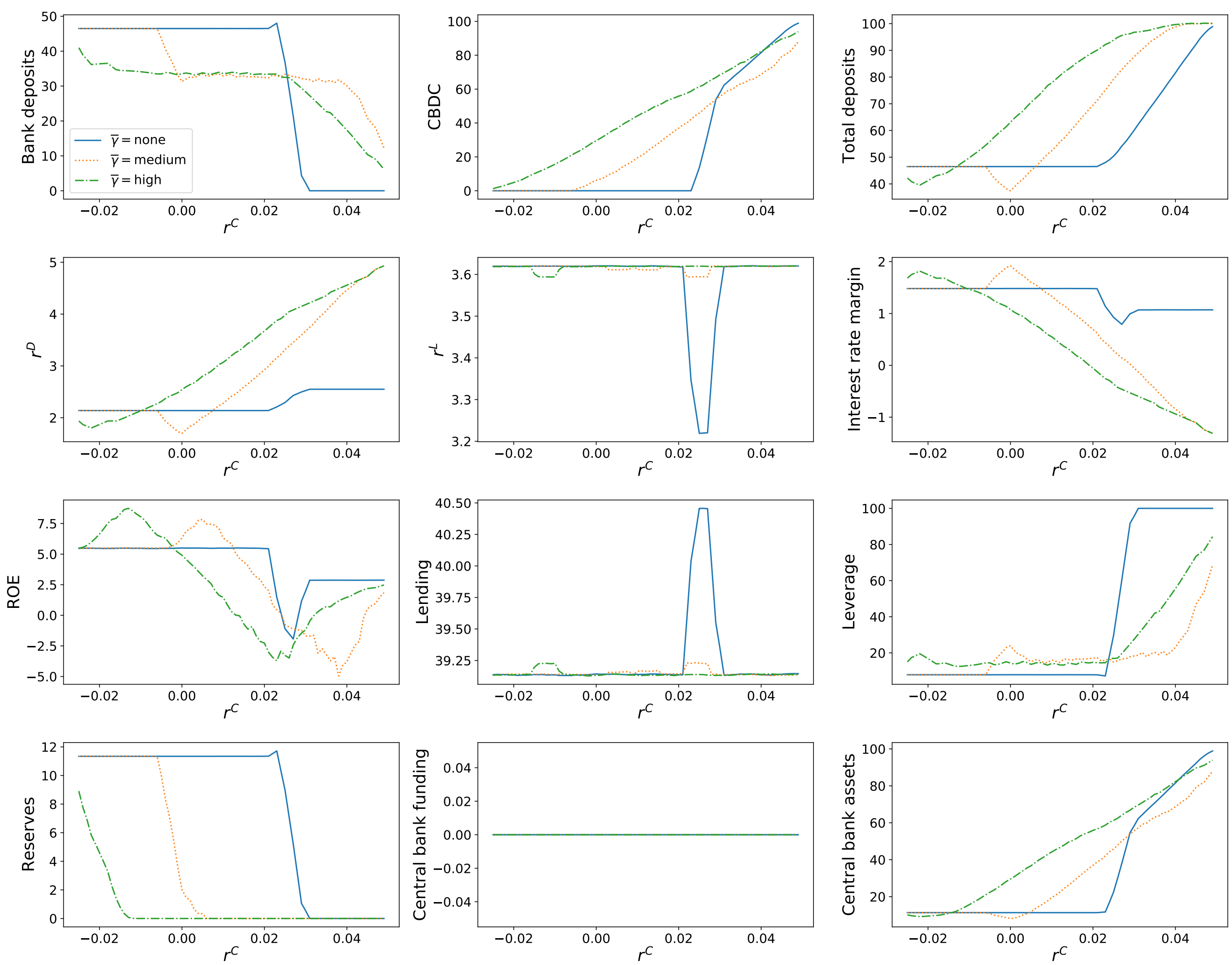

Figure 7. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C and the maximum households' technological preference $\bar{\gamma}$.

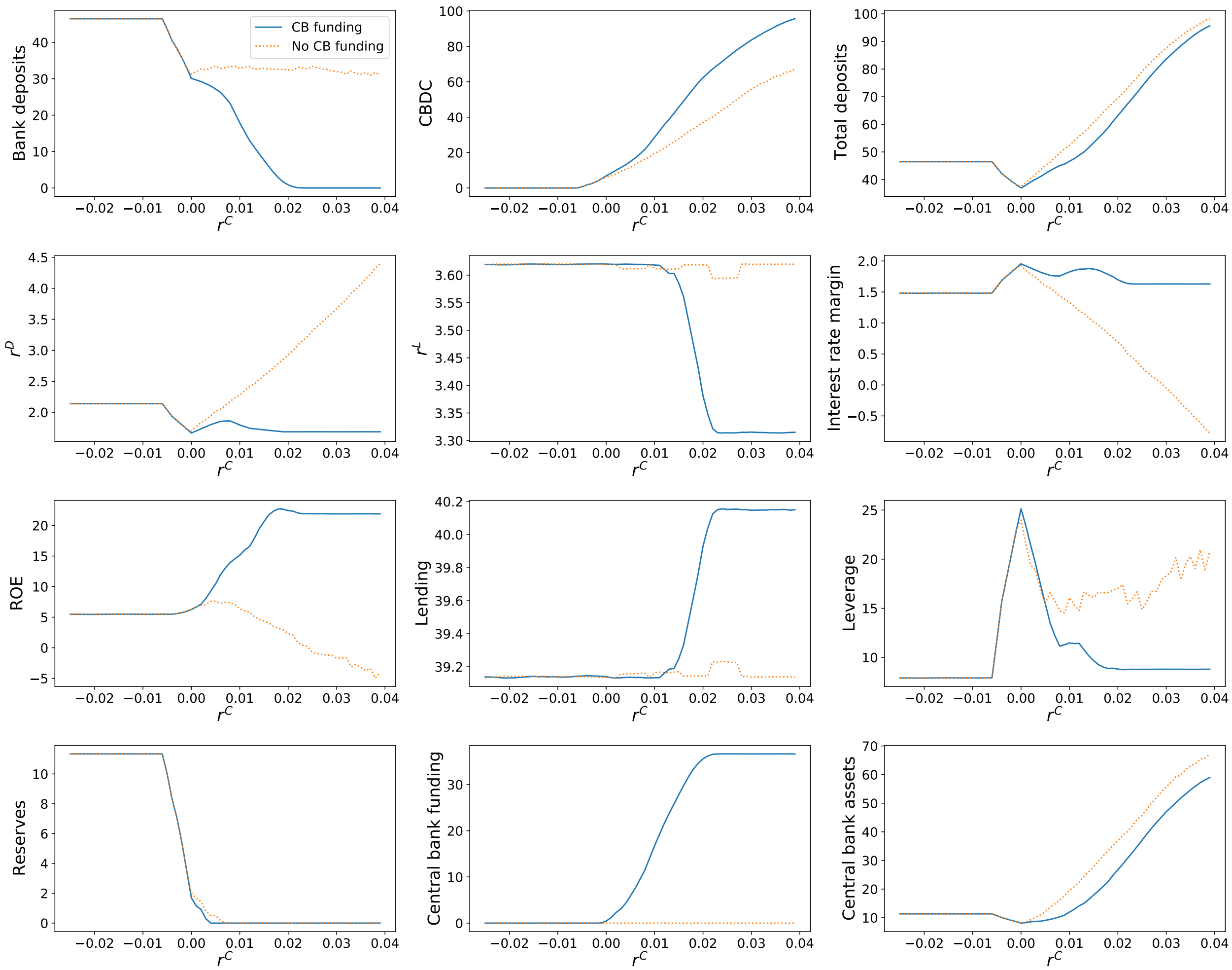

Figure 8. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C and the maximum households' technological preference $\bar{\gamma}$ set to a medium level. It compares the scenarios in which we allow or not the central bank to compensate the commercial bank for the loss in deposits.

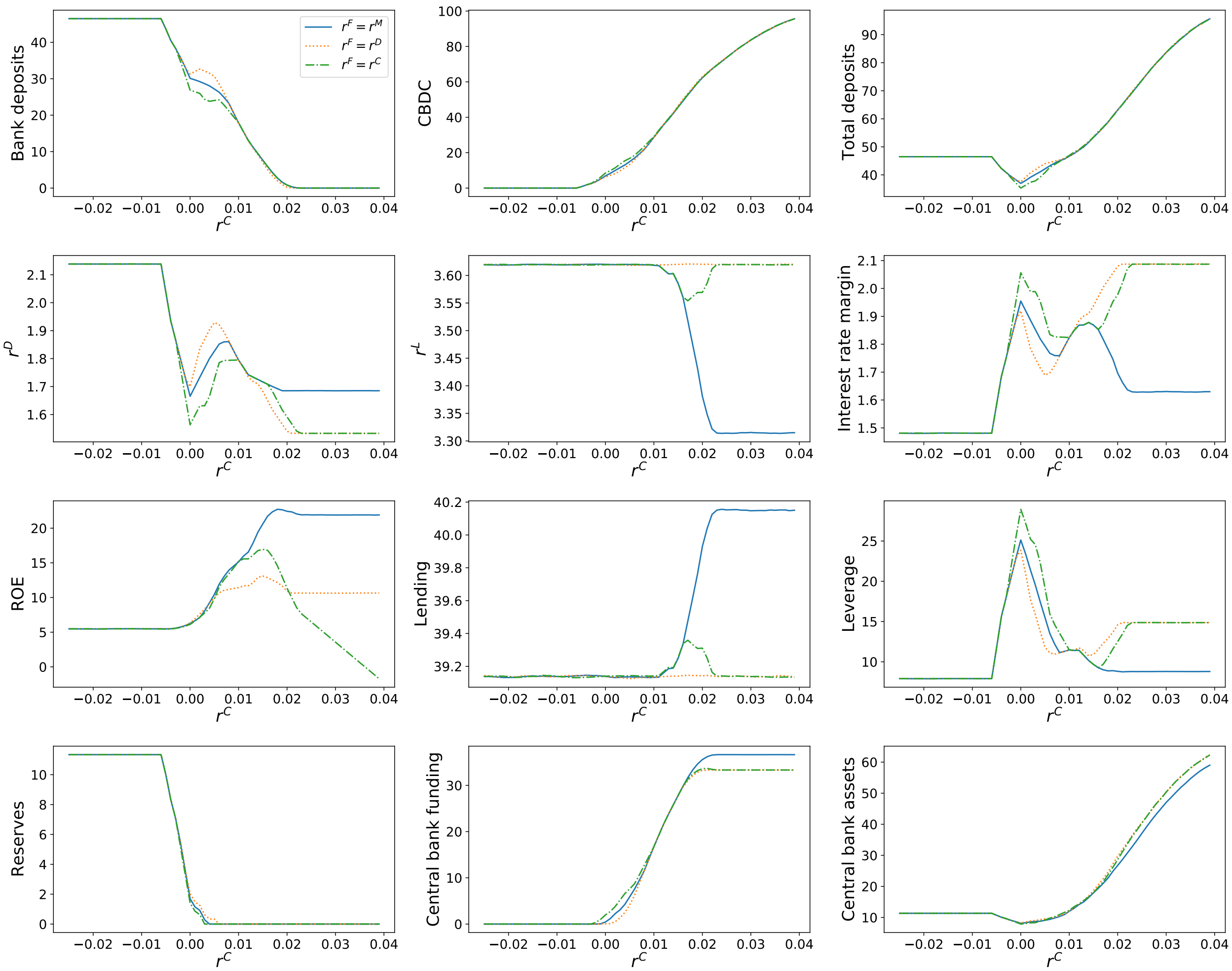

Figure 9. This figure shows the effects of introducing a CBDC for different levels of CBDC interest rate r^C and the maximum households' technological preference $\bar{\gamma}$ set to a medium level. It compares the scenarios in which we allow the central bank to compensate the commercial bank for the loss in deposits with different funding interest rates.