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Optimal Central Banking Policies: Envisioning the Post-Digital Yuan Economy with Loan Prime Rate-setting

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Abstract

We develop a DSGE model with cash and digital currency to study the financial stability properties of two potential central banking policies in China. Specifically, a Loan Prime Rate (LPR)-setting policy function and central bank digital currency (CBDC) implementation are examined. Distinguish between a benchmark model and a "Post-CBDC world", we Bayesian-estimate the model. Post-CBDC implementation, we find macroeconomic variables to display greater procyclicality to real shocks. However, we also find a potential LPR-setting policy to exhibit an improved stabilization property in the post-CBDC world. We uncover an optimal design of LPR policy function, which targets more specifically housing and capital asset markets, as well as the growth in CBDC. This suggests a potential policy complementarity between these two seemingly unrelated central banking policies in the financial stability agenda of China going forward.

JEL Classification Numbers: E4, E52, E58, C11

Keywords: China, Digital Currency, Loan Prime Rate, Monetary Policy, Bayesian DSGE models.

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1 Introduction

The economy of China has experienced significant monetary and financial developments after years of high economic growth to become the second largest economy in the world. As financial deepening takes place, the needs for an expanded suite of central banking policies have also increased. In recent years, two notable, yet underexposed policies have been introduced by the People's Bank of China (PBOC): (i) the Loan Prime Rate (LPR) reform; and the experimentation of the (ii) Digital Currency Electronic Payment (DCEP), commonly dubbed as the Digital Yuan or China's central bank digital currency (CBDC).

On the former, PBOC has traditionally used the 7-day reverse repo and the Medium-term Lending Facility (MLF) rates to support its open market operations in implementing monetary policy. However, given China's market size and the wide disparity across regions geographically, it is perhaps unsurprisingly that active adjustments of these rates have been less than satisfactory in curbing high domestic credit growth. Indeed, as argued in studies such as Chen et al. (2018) and Chang et al. (2019), conventional monetary policy transmission mechanisms in China appear to be effective via money supply growth adjustment instead of a Taylor Rule-style interest rate targeting. As an effort to have more direct influence on the market interest rates (so as to lower overall borrowing costs), the post-August 2019 LPR reform sees the official announcement of the benchmark LPR rate being centralized at the hands of the National Interbank Funding Center, authorized by the PBOC. By construction, the benchmark LPR is calculated based on an adjusted average of the preferential lending rates quoted by some of the largest commercial banks in the Chinese economy, which is then used as a reference lending rate by the rest of the lenders in the economy. In essence, the new LPR provides the PBOC with a more direct oversight and control of the market lending rate—albeit one that is based on targeted advisory, guidance, and consultation of panel banks, many of which are State-owned—similar to an official policy rate, but with the characteristics of a pseudo-macroprudential regulation tool (due to its direct targeting of market loan rates).

On the latter, the PBOC has recently initiated on some selected Digital Yuan pilot programmes, with the CBDC being a centralized fiat money fully backed by the PBOC.[1] In spite of a broad taxonomy on the potential characteristics of a CBDC, central bank digital currency refers to "any electronic money, at the liability of a central bank that can be used to settle payments, or as a store of value" (Meaning et al., 2018), and a Central Bank's interest in it often rests with the advantages associated the blockchain and distributed ledger technology (DLT), i.e. the record-keeping and sharing database architecture that ensures integrity through the use of consensus-based validation protocols and cryptographic signatures. Moreover, by virtue of being digital money, payments/transactions made using CBDC would theoretically save the economy from various paper money velocity-based transaction costs associated with the frequency of cash changing hands (Barrdear and Kumhof, 2016; Berentsen and Schär, 2018). Indeed, by replacing cash with CBDC, the central bank will then be in a position to pay negative interest rates on its liabilities in overcoming the "zero lower bound" problem (Buiter, 2009; Agarwal and Kimball, 2015; Fischer, 2016), and overcoming the crime and tax evasion issues raised in Rogoff (2015). As such, in a large economy such as China, where unaccounted monetary velocity and impulse could potentially exacerbate economic volatility, there is also a financial stability angle to CBDC. In fact, apart from the various benefits associated with CBDC, the increasing attention garnered by private digital currencies domestically (at one point China accounted for 90% of global trades in Bitcoins before the well-publicized 'Cryptocurrency Ban" in 2017) posing a greater risk to passive central banking (Bordon and Levin, 2017), has prompted the PBOC to be at the forefront of the initiative in introducing a CBDC, alongside the Swedish Riksbank (Agur et al., 2020).

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[1] At the point of writing, the PBOC's Digital Currency Electronic Payment system remains in an experimental stage, though it is widely believed that the issuance will be via a 2-tier system (similar to existing paper currency), where commercial banks would deposit reserves with the PBOC in order to issue Digital Yuan to end users. Essentially, Digital Yuan is therefore an account-based CBDC (Bordo and Levin, 2017), as it ultimately counts against the Central Bank liabilities in a roundabout way. Based on the key properties of the money taxonomy of Bech and Garratt (2017), other key features include centralization and peer-to-peer (with a certain degree of controlled anonymity to the users). It is also worth pointing out that it is the objective of PBOC to have CBDC existing together with the current paper-based fiat currency, instead of a complete phase out.

In this article, we contribute to the literature by developing a dynamic stochastic general equilibrium (DSGE) model with cash and digital currency, both being used as payment options by households for consumption. The former is subject to cash velocity-related transaction costs similar to Barrdear and Kumhof (2016). At its core, without the different currencies and central banking policies, the model has a "housing as collateral for commercial bank loan" set-up similar to China-based studies such as Minetti et al. (2019), Liu and Ou (2020). To examine the effects brought about by a full implementation of CBDC (beyond that of a one-off deterministic shock to money stocks), we distinguish between a benchmark model and a "Post-CBDC world" model, where prior to the implementation of CBDC the households pay digitally using private digital currency (PDC), albeit with a significant holding/access cost due to the direct trading using Chinese Yuan within China being restricted since 2018.[2] As such, unlike cryptocurrency competition model of Fernández-Villaverde and Sanches (2019), there is only one type of PDC in our model (supplied by an exogenous fixed quantity), though its price is a source of stochastic shocks to the economy. Indeed, the treatment of PDC in our benchmark model has a similar spirit to Hong et al. (2018), Schilling and Uhlig (2019), where PDC coexists and competes with cash as payment means.[3,4]

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[2] This benchmark is necessary to support a meaningful investigation, instead of a case where we simply move from an economy without digital payment option to one with CBDC (for which then most policy effects are obvious). Indeed, despite the ban on private cryptocurrency trading in early 2018, reports are abundant that Chinese buyers have resorted to not only offshore exchange platforms in neighboring countries but also over-the-counter trading platforms like Huobi, OKEx and OTCBTC, which link individual buyers directly to sellers. Indeed, alternative PDCs, such as USD Tethers, have seen their trading volume ballooned since 2017. See, for instances, SCMP (2018) and Bloomberg (2019). These are notwithstanding the fact that China remains the largest host of bitcoin mining (65% of Global Bitcoin Hashrate), according to Cambridge Centre for Alternative Finance, https://cbeci.org/mining_map/methodology.

[3] As would become clear later, despite of the large access cost, the combination of the transactional advantages of virtual money (not subject to velocity-based transaction costs), as well as the possible price appreciation of PDC, mean households will continue to hold PDC as both a means of payment and a digital financial asset (Giudici et al., 2020). From a macroeconomic perspective, the market price of PDC also serves as a potential source of volatility to the economy, which facilitates the use of actual Bitcoin prices data to Bayesian-estimate the model. Indeed, to preview, the variance decomposition analysis results reveal that the contribution of PDC price shocks to the economy is largely immaterial and self-contained.

[4] Of course, as pointed out in studies such as Gans and Halaburda (2015), Yermack (2015), we recognize that the debate about whether PDC can truly function as a medium of exchange remains largely contentious, and often differs greatly in terms of the nature of the digital currency. For our analytical purposes, we follow the standard convention in the literature and assume that it can be used equivalently to official monies in making purchases.

The benchmark model is a Bayesian estimate for the Chinese economy. Prior to CBDC implementation, there are two policy tools available to the Central Bank: (i) the money supply (M2) growth rule, as in Chang et al. (2019); (ii) the loan prime rate (LPR). In the post-CBDC world, quantities of CBDC would then become households' choice of monetary assets too (determined from households' optimization problem), with its interest rate being set by the Central Bank. To preview, initially, consistent with the current DCEP design for Digital Yuan (where CBDC is exchanged at par with cash), we assume the CBDC policy rate to be set as a discount of the deposit rate. However, in the subsequent examination of welfare-optimal central banking policies, we find interior solutions for both price and output stabilization mandates in the setting of CBDC rate. For the LPR-setting, although there does not exist a welfare-optimality case for LPR to be set using a policy reaction function, we do uncover non-zero welfare-optimal policy mandates with respect to growth in asset markets. Indeed, we also find a non-zero welfare-optimal policy mandate of LPR-setting with respect to the growth of the stock of CBDC, hence suggesting a potential interaction of these two seemingly unrelated central banking policies in the financial stability agenda of the Chinese economy going forward.

Given these, our article is most closely related to the growing literature examining CBDC and its implementation, notably Barrdear and Kumhof (2016), which relies mainly on results from numerical experiments. Non-exhaustively, in this literature that contributes to the understanding of CBDC as "Reserves for All" (Niepelt, 2020), other studies (mainly analytical) include Agur et al. (2021), which analytically identifies an optimal design of CBDC based on individuals' preferences over anonymity and security; Keister and Sanches (2019), which analytically identifies a trade-off between welfare gains and other negative effects (investment reduction, bank-funding cost increase) when CBDC competes directly with bank deposits; Andolfatto (2021), which finds CBDC to potentially promote bank lending activity based on a two-period-lived overlapping generation model with private monopoly banks; Fernández-Villaverde et al. (2020), whose model specifies an initial equivalence between the central bank investing in both the storage technology of a CBDC and making a loan to investment banks (competing for the same funds from private agents), but finds the former to be more stable during financial panic; Jia (2020), which studies the substitution effect between CBDC and physical capital stock and find the implementation of negative interest payments on CBDC to have adverse effect on capital investment and output, despite being consumption-enhancing.

In comparison to these studies, our study, while more numerical in nature (hence with limited analytical tractability in certain transmission mechanisms), examines the implementation of CBDC in a much wider scope (in the context of the overall Chinese economy), as well as its interactions with other central banking policies. To this extent, we also contribute to the literature examining central banking policies in China (Chang et al., 2019; Minetti and Peng, 2018; Minetti et al., 2019). By utilizing the actual data-based Bayesian estimation technique, we contribute further understanding of the macroeconomic cyclicality of China in recent years, especially in the context of a model economy with combined monetary and housing markets influenceable the three different central banking polices considered. More importantly, based on the estimated model, we then identify welfare-optimal policy designs for the LPR-setting and CBDC policy rate. In an environment where majority of the global central bankers are proceeding with caution despite significant policy interest towards CBDC (Barontini and Holden, 2019; Boar et al., 2020), and that there being sceptics of a potential risk of CBDC to money stability[5], we believe our study, which at a minimum shows the existence of a welfare-optimal design for LPR-setting and CBDC policy rules, would help to build further understanding of their roles in maintaining financial stability in China. Indeed, although we find that the introduction of CBDC appears to deepen the procyclicality of macroeconomic variables to real shocks, a potential LPR-setting policy appears to have some degree of policy complementarity with CBDC to mitigate this in the post-CBDC world.

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[5] For instance, in the study of Gross and Siebenbrunner (2019), they conclude that the introduction of CBDC will cause liquid funding (reserves) needs to vanish, hence leading to conventional interest-based monetary policy totally losing its impact on the economy.

The remainder of our article is as follows. Section 2 presents the theoretical model in both the benchmark case and the post-CBDC world, followed by a discussion of the equilibrium solutions in Section 3. Section 4 explains the calibration and estimation strategy. Section 5 then presents and evaluates the results, followed by welfare-optimal analysis to inform policy designs. Section 6 concludes the article.

2 Theoretical Model

The model economy consists of a continuum of individuals, who hold cash, private digital currency (PDC), and CBDC (post-implementation) to pay for consumption of final goods. Final goods are produced by a representative retailer using intermediate goods (IG) produced by IG producers (owned by individuals), who employ labor supplied by individuals and capital rented from a capital good producer. The capital producer also rents out its capital goods to a price-taking representative housing supplier, which produces housing units to meet the demand of individuals. To pay wages in advance, the IG firms borrow from a commercial bank, which in turn requires the IG firms to use housing units of their owners as collaterals. To model loan prime rate (LPR) as a policy function, we assume the loan-to-value ratio to be fixed by laws, and any variation in loan demands to be driven by the LPR set directly by the Central Bank. Prior to CBDC implementation, in addition to LPR-setting, the Central Bank implements its monetary policy using a M2 (cash plus deposits) quantity supply rule, following Chang et al. (2019). Lastly, there is also a government, whose expenditure is financed by taxes and issuance of bonds, held by individuals and the Central Bank. The presence of the government and domestic bond market provides a straightforward source of finance for the one-off implementation of CBDC into the economy (where the ‘new’ central bank liabilities of CBDC is met by ‘flow injection’ from the government).

By design, the three types of money, as well as deposits, are not equivalent in our model, unlike the set-up in Brunnermeier and Niepelt (2019). The key differences are summarized in

Table 1. To capture the inefficiency/inconvenience associated with the settlement, storage, carrying, and payment of notes and coins from one party to another, cash is assumed to incur a monetary transaction cost tied to the velocity of circulation (Schmitt-Grohé and Uribe, 2004; Barrdear and Kumhof, 2016). This cost is not incurred by the usage of all digital currencies, due to the vast efficiency and costless settlement in DLT (Benos et al., 2017). Nevertheless, for China, PDC is costly to access, with the cost assumed to be an increasing function to the ratio of non-PDC to total money stock (to capture the network externality introduced by Agur et al., 2021). The returns to PDC are nonetheless non-zero, due to the potential market price appreciation of PDC. Post-CBDC implementation, the quantity of CBDC-holding by individuals is determined by their optimization problem, though in line with the CBDC literature, we assume the returns of CBDC to be at a discount of the private deposits rate. Lastly, we assume both the monetary transaction cost and accessibility costs are individual-specific, and individuals fully observe them.

2.1 Individuals

There is a continuum of individuals $h \in (0, 1)$ with homogeneous preferences in consumption, labor supply, and assets-holding. Each individual h supplies labor quantity, N_{ht}, to intermediate goods (IG) producers, and owns an IG firm i (for simplicity, $N_{ht} \neq N_{it}$). In each period, individuals make their housing stocks available, H_{ht}, to the IG firm they owned, so as to be used by the firm as a collateral in its borrowing. In addition, individual h holds cash (M^F_{ht}), digital currency [initially, only PDC, M^B_{ht}, is available in the benchmark case; subsequently, CBDC, M^{CD}_{ht}, is also made available as a choice variable in the full model], and observes the monetary transaction costs associated with cash (s^F_t), as well as the cost of access incurred for holding PDC, f^B_t. The presence of these costs result in the individual choosing a $\xi_{ht} \in (0, 1)$ fraction of final-goods consumption, C_{ht}, to be paid by cash, and the remaining $1 - \xi_{ht}$ to be paid by digital currency. The individual also holds bank deposits, D_{ht} and government bonds, B^{HD}_{ht}.

At the beginning of each period, a typical individual h maximizes discounted life-time utility,

$$U_t^h = \mathbb{E}_h \sum_{t=0}^{\infty} \beta^t \varepsilon_t^C \left[\begin{array}{c} \ln C_{ht} + \eta_H \ln H_{ht} \\ +\eta_M \ln(\frac{M_{ht}}{P_t}) - \eta_N \frac{(N_{ht})^{1+\varsigma_N}}{1+\varsigma_N}, \end{array} \right], \tag{1}$$

where $\mathbb{E}_t$ is the expectation operator at time t, $\beta \in (0,1)$ is the subjective discount factor, $\varsigma_N > 0$ denotes the inverse Frisch elasticity of working, $\eta_H, \eta_M > 0$ are the utility weights for housing and money-holdings, and ε_t^C is a stochastic preference shock where $\varepsilon_t^C = (\varepsilon_0^C)^{1-\rho_C}(\varepsilon_{t-1}^C)^{\rho_C} \exp(v_t^C)$, where $\varepsilon_0^C > 0$, $\rho_C \in (0,1)$ is the associated AR(1) coefficient, and v_t^C the normally distributed stochastic shock with zero mean and a constant variance (σ_C^2), by choosing sequences of real consumption (C_{ht}), labor supply (N_{ht}), housing (H_{ht}), cash-payment share (ξ_{ht}), and the quantity of cash (M_{ht}^F), PDC (M_{ht}^B), deposits (D_{ht}), and bonds (B_{ht}^{HD}), subject to the budget constraint,

$$\begin{aligned} & P_t C_{ht} + s_{ht}^F \xi_{ht} P_t C_{ht} + s_{ht}^D (1-\xi_{ht}) P_t C_{ht} + P_t^H \Delta H_{ht} + B_{ht}^{HD} \\ & + M_{ht}^F + (1-f_{ht}^B) e_{t+1} \mathbb{E}_t P_{t+1}^B M_{ht}^B + D_{ht} \leq M_{ht-1}^F + e_t P_t^B M_{ht-1}^B + (1+i_{t-1}^D) D_{ht-1} \\ & + (1+i_{t-1}^B) B_{ht-1}^{HD} + P_t (w_t N_{ht} - T_{ht}) + \Pi_t^R + \Pi_t^K + \Pi_t^H, \end{aligned} \tag{c2}$$

where e_t is the nominal exchange rate (assumed to grow at a constant rate, $1+g_e$, as in Chang et al., 2015), P_t^B is the market price of PDC ($\mathbb{E}_t e_{t+1} P_{t+1}^B M_{ht}^B$ therefore gives the expected market value of PDC to be received by individual h), P_t the domestic price level, $P_t^H \Delta H_{ht}$ is the change in the housing stock value, i_t^D the deposit rate, i_t^B bond rate, w_t the real wage, T_{ht} a lump-sum tax, Π_{ht}^R, Π_{ht}^K, Π_{ht}^H are the dividends/profit shares from retail firms, capital good producer, and housing supplier.[6]

For the cash-based transaction cost, s_{ht}^F, we follow the velocity-based specification of

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[6] As seen later in the *Housing Supply* section, the change in housing stock of individuals can be expressed as, $P_t^H \Delta H_{ht} = P_t^H [H_{ht} - (1 - \delta_H - \varphi\varkappa) H_{ht-1}]$, which is influenced by depreciation (δ_H) and the possibility of a collateral confiscation due to loan default $(\varphi\varkappa)$. Second, note also that the commercial bank collectively owned by the individuals makes zero profits.

Schmitt-Grohé and Uribe (2004), Barrdear and Kumhof (2016). Specifically,

$$s^F_{ht} = s(\upsilon^F_{ht}), \text{ where } \upsilon^F_{ht} = \frac{\xi_{ht} P_t C_{ht}}{M^F_{ht}},$$
$$\text{with } s(\upsilon^F_{ht}) = s_{0,t} + A_F \upsilon^F_{ht} + B_F/\upsilon^F_{ht} - 2\sqrt{A_F B_F}, \tag{2}$$

which satisfies the properties of increasing in υ^F_{ht}, non-negative and twice continuously differentiable. For this specific functional form, $A_F > \underline{A}$, $B_F > \underline{B}$ are assumed, where $\underline{A}, \underline{B} > 0$ correspond to the parameter values that give the satiation velocity level of cash-holding, $\underline{\upsilon}^F = \sqrt{\underline{B}/\underline{A}} > 0$ (see Schmitt-Grohé and Uribe, 2004). These ensure that $\upsilon^F_{ht} > \underline{\upsilon}^F$ holds at all time. In addition, $s_{0,t} > 0$ is assumed to follow an AR(1) process, $s_{0,t} = (\tilde{s}_0)^{1-\rho_s}(s_{0,t-1})^{\rho_s} \exp(\upsilon^s_t)$, with $\tilde{s}_0 > 0$ being the non-zero steady-state transaction cost, $\rho_s \in (0,1)$ and υ^s_t denote the persistence and random error terms respectively. Note that if $s_{0,t} = 0$, then the velocity of cash, $\upsilon^F_{ht} = \sqrt{A_F B_F}/A_F \; \forall t$, i.e. constant at all time. In other words, this specific shock can also be interpreted as an indirect measure of all noises associated with paper money impulses in the economy.

For the access/holding cost function of PDC, $f^B_{ht} \in [0,1]$, in the absence of corresponding references, the following is specified:

$$f^B_{ht} = f^B_h(\chi^B_{ht}), \text{ where } \chi^B_{ht} = \frac{M^B_{ht}}{M_{ht}}, \text{ with } f^B_{ht}(\chi^B_{ht}) = f^B_0\left(\frac{1-\chi^B_{ht}}{1-\tilde{\chi}^B}\right)^{\zeta_1}, \tag{3}$$

where $\zeta_1 \geq 0$. Although the economic rationale of f^B_{ht} is consistent with the 'regulatory hostile' landscape in China towards PDC, the specification of (3) is consistent with the literature. Specifically, it captures the network effects of Gans and Halaburda (2015), Agur et al. (2019): the more PDC usage widens (as measured by its share in individual's currency stock holdings, χ^B_{ht}), the less costly it is for said individual due to greater acceptance. Finally, for the CBDC introduced later, M^{CD}_{ht}, both the transaction and access costs are zero.

As shown in Appendix A, solving the individuals' intertemporal optimization problem yields first-order conditions:

$$\frac{\mathbb{E}_t C_{ht+1}}{C_{ht}} = \mathbb{E}_t \left\{ \frac{\beta(1+i_t^D)}{(1+\pi_{t+1})} \frac{\varepsilon_{t+1}^C}{\varepsilon_t^C} \left[\frac{1 + s_{0,t}(2\xi_{ht} - 1) + 2\xi_{ht}(A_F \upsilon_{ht}^F - \sqrt{A_F B_F})}{1 + s_{0,t+1}(2\xi_{ht+1} - 1) + 2\xi_{ht+1}(A_F \upsilon_{ht+1}^F - \sqrt{A_F B_F})} \right] \right\}, \tag{4}$$

$$\xi_{ht} = \sqrt{\frac{B_F (m_{ht}^F)^2}{C_{ht}(A_F C_{ht} + m_{ht}^F)}}, \tag{5}$$

$$\frac{w_t}{\eta_N (N_{ht})^{\varsigma_N}} = C_{ht} \left[1 + s_{0,t}(2\xi_{ht} - 1) + 2\xi_{ht}(A_F \upsilon_{ht}^F - \sqrt{A_F B_F}) \right], \tag{6}$$

$$\begin{aligned} &\eta_{H,t} C_{ht} \left[1 + s_{0,t}(2\xi_{ht} - 1) + 2\xi_{ht}(A_F \upsilon_{ht}^F - \sqrt{A_F B_F}) \right] \\ &= (p_t^H H_{ht}) - \mathbb{E}_t \left[\beta \frac{\varepsilon_{t+1}^C}{\varepsilon_t^C} (1 - \delta_H - \varphi \varkappa) \frac{(1+\pi_{t+1})}{(1+i_t^D)} p_{t+1}^H H_{ht} \right], \end{aligned} \tag{7}$$

$$m_{ht}^F = \mathbb{E}_t \left\{ \begin{array}{c} \left(1 - e_t P_{t+1}^B + \frac{e_{t+1} P_{t+1}^B}{1+i_t^D}\right) \frac{1}{A_F} \\ + \frac{f_{ht}^B}{A_F} \left[e_{t+1} P_{t+1}^B (1 - \zeta_1 \chi_{ht}^B) - \frac{\zeta_1 \left(\chi_{ht}^B\right)^2}{(1-\chi_{ht}^B)} \right] + \frac{B_F}{A_F} \end{array} \right\}^{-0.5} \xi_{ht} C_{ht}, \tag{8}$$

$$m_{ht}^B = \mathbb{E}_t \left\{ \begin{array}{c} 1 - \frac{1}{\zeta_1 \chi_{ht}^B} \\ + \frac{1}{\zeta_1 f_{ht}^B} \left[1 + \frac{(e_{t+1}/e_t)}{(1+i_t^D)} \right] \end{array} \right\}^{-1} \left[\frac{\eta_M w_t (1+i_t^D)}{\zeta_1 \eta_N (N_{ht})^{\varsigma_N} f_{ht}^B} \frac{(e_{t+1}/e_t)}{e_{t+1} P_{t+1}^B} \right], \tag{9}$$

where $m_{ht}^F = M_{ht}^F / P_t$, $m_{ht}^B = M_{ht}^B / P_t$ are the real values of the currencies, $\mathbb{E}_t(1 + \pi_{t+1}^H) = P_{t+1}^H / P_t^H$ is the expected inflation rate of housing prices, and $\mathbb{E}_t(1 + \pi_{t+1}) = P_{t+1}/P_t$ is the expected inflation rate. (4) is the Euler equation, which in this model is influenced by the payment transaction cost of cash; (5) shows the optimal fraction of payment made using cash, ξ_{ht}; (6) is individual h's labor supply equation that equates marginal utility of leisure to that of consumption; (7) presents the intra-temporal substitution condition between the marginal demand for housing and marginal consumption of final goods; (8) is individual h's real demand function for cash, which is proportionate to the real value of consumption paid using cash; (9) is the real demand function for PDC, which depends on the access/holding cost, its expected effective market valuation ($e_{t+1} P_{t+1}^B$), as well as the returns from 'competing' sources such as deposits and real wages.

In terms of PDC supply, unlike Schilling and Uhlig (2019), we abbreviate from detailed modeling of the mining protocols associated with cryptocurrency production and simply set $M_t^B = A_t M_0^B$, where an exogenously given constant stock of PDC (similar to Garratt and Wallace, 2018) is augmented by the domestic productivity level (to ensure balanced growth in steady state). Indeed, with China still accounting for over half of the global Bitcoin hash rate despite the government clampdown post-2017, it is a reasonable specification to make for the initial benchmark case where payments using digital currency is an option—albeit a costly one—for individuals. For the market prices of PDC, existing empirical-based studies on cryptocurrency prices tend to be direct applications of volatility modeling to daily price data. Given the 'lengthier', monthly context of time in our estimated model, the issues commonly plaguing high-frequency data—which necessitate a volatility modeling approach—are not a concern. However, the random-walk nature of asset-pricing needs to be accounted for, which the calls for the PDC spot prices, P_t^B, to evolve according to:

$$P_{t+1}^B = P_t^B + \varepsilon_t^B, \text{ where } \quad \varepsilon_t^B = (1-\rho_B)\tilde{\varepsilon}^B + \rho_B \varepsilon_{t-1}^B + v_t^B, \quad v_t^B \tilde{} N(0, \sigma_B^2), \tag{10}$$

where $\rho_B \in (0,1)$ is the persistence of the ε_t^B term, and v_t^B is i.i.d. standard error with a normal distribution. Given that (10) also implies $\Delta P_{t+1}^B = \varepsilon_t^B$, if $\rho_B = 0$, then the change in spot price of PDC would follow a random walk process with a positive drift of $\tilde{\varepsilon}^B$ over time. Nevertheless, given that (10) can also be written as $P_{t+1}^B / P_t^B = 1 + (\varepsilon_t^B / P_t^B)$, in a steady-state equilibrium, $\tilde{\varepsilon}^B = 0$ must hold, which implies a fundamental/intrinsic value of zero——consistent with the assertion of studies such as Cheah et al. (2018). In our views, given the relative ease of access to the prices and trading volumes of cryptocurrency, this specification allows us to take advantage of these data (as a proxy for PDC) to Bayesian-estimate the model.

2.2 Retail and production sector

There is a representative retailer who aggregates all the IGs [Y_{it}, with $i \in (0,1)$] into composite homogenous final goods (Y_t) using the standard Dixit-Stiglitz (1977) technology,

$$Y_t = \left\{ \int_0^1 [Y_{it}]^{(\theta-1)/\theta} di \right\}^{\theta/(\theta-1)}, \tag{11}$$

where $\theta > 1$ is the constant elasticity of substitution between IGs. Let P_{it} denotes the IG price of product i, the demand functions for each IG is

$$Y_{it} = (\frac{P_{it}}{P_t})^{-\theta} Y_t, \tag{12}$$

with the corresponding aggregate price index, $P_t = \left[\int_0^1 (P_{it})^{1-\theta} dj \right]^{1/(\theta-1)}$.

The IGs are supplied by a continuum of monopolistically competitive IG firms, $i \in (0,1)$, each producing a differentiated IG, Y_{it}, using a Cobb-Douglas technology,

$$Y_{it} = Z_t^Y (K_{it}^Y)^{\alpha} (A_t N_{it})^{1-\alpha}, \tag{13}$$

where $\alpha, \gamma \in (0,1)$, N_{it} is the labor input, K_{it}^Y is capital goods rented by firm i at a cost, P_t^{KY}, from the capital good producer. Collectively, total capital goods rented by all IG producers are given by $K_t^Y = \int_0^1 K_{it}^Y di$. In line with the emerging-market business cycle literature (Aguiar and Gopinath, 2007; García-Cicco et al., 2010), production is influenced by both a labor-augmenting technology, A_t, and a Hicks-neutral technology, Z_t^Y, that are common to all firms. The former is assumed to grow at a rate of $1 + g_{At} = A_t/A_{t-1}$ (as in Chang et al., 2015), whereas the latter is assumed to follow an AR(1) process, $Z_t^Y = (\tilde{Z}^Y)^{1-\rho_{ZY}} (Z_{t-1}^Y)^{\rho_{ZY}} \exp(v_t^{ZY})$, with $\rho_{ZY} \in (0,1)$ and v_t^{ZY} denote the persistence and random error terms respectively. In each period t, cost minimization in a symmetric equilibrium gives the real marginal cost, mc_t, $\forall i$,

$$mc_t = \Phi_Y(\frac{P_t^{KY}}{P_t})^{\alpha}(\frac{w_t}{A_t})^{1-\alpha}, \text{ where } \Phi_Y = \alpha^{-\alpha}(1-\alpha)^{\alpha-1}, \text{ which also implies} \tag{14}$$

$$\frac{w_t}{(P_t^{KY}/P_t)} = (\frac{1-\alpha}{\alpha})\frac{K_{it}^Y}{N_{it}}. \tag{15}$$

IG firms set their prices in a Calvo-Yun type staggered pricing (Calvo, 1983; Yun, 1996). Specifically, in each period an IG firm i faces a constant probability ω to set its price according to a Smets-Wouters (2003) type of indexation rule, $P_{it+s} = P_{it}(\frac{P_{t+s-1}}{P_{t-1}})^{\varrho}$, $\varrho \in (0,1)$, and a probability $1-\omega$ in re-optimizing its price. The optimal reset price, P_{it}^*, solves:

$$\mathbb{E}_i \sum_{s=0}^{\infty} (\varpi\beta)^s \left\{ V_{t,s} \left[\frac{P_{it}^*}{P_{it+s}} - \frac{\theta}{(\theta-1)} mc_t \right] Y_{it+s} \right\} = 0, \tag{16}$$

with the IG price in a given period, $P_{it} = \left[\omega P_{it-1}^{1-\theta} + (1-\omega)(P_{it}^*)^{1-\theta}\right]^{1/(1-\theta)}$. Assuming symmetric equilibrium, substituting the indexation rule into (16), and then log-linearizing it and the IG price equation, we derive a Galí-Gertler (1999) style hybrid New Keynesian Phillips curve (NKPC):

$$\hat{\pi}_t = \frac{\beta}{1+\beta\varrho}\mathbb{E}_t\hat{\pi}_{t+1} + \frac{\varrho}{1+\beta\varrho}\hat{\pi}_{t-1} + \frac{(1-\varpi)(1-\varpi\beta)}{\varpi(1+\beta\varrho)}\widehat{mc_t} + \hat{\varepsilon}_t^{\pi}, \tag{17}$$

which relates the log-deviation of inflation (from the steady state), $\hat{\pi}_t$, to both the past and future inflation, as well as the log-deviation in real marginal cost, $\widehat{mc_t}$. $\hat{\varepsilon}_t^{\pi}$ is a mean-zero 'cost-push' shock, which follows an AR(1) process, $\varepsilon_t^{\pi} = (\varepsilon_{t-1}^{\pi})^{\rho_{\pi}} \exp(v_t^{\pi})$, where $\rho_{\pi} \in (0,1)$ and v_t^{π} denote the persistence and random error terms respectively.

2.3 Housing supply

There is a perfectly competitive, price-taking representative firm that serves as a housing supplier in the economy. At the beginning of each period, the housing supplier pays P_t^{KH}

to rent quantity of capital goods, K_t^H, to serve as inputs to produce new housing units (in flow terms, as in Iacoviello and Neri, 2010), IH_t, using the transformation technology,

$$IH_t = Z_t^H (K_t^H)^{\iota}, \tag{18}$$

where $\iota \in (0,1)$, and Z_t^H follows an AR(1) process, $Z_t^H = (\tilde{Z}^H)^{1-\rho_{ZH}} (Z_{t-1}^H)^{\rho_{ZH}} \exp(v_t^{ZH})$, where $\rho_{ZH} \in (0,1)$ and v_t^{ZH} denote the persistence and random error terms respectively.

Faced with a profits function, $\Pi_t^H = P_t^H IH_t - P_t^{KH} K_t^H$, the housing supplier maximizes profits by choosing quantity K_t^H, which yields the first-order condition:

$$\frac{P_t^H}{P_t^{KH}} IH_t = \frac{K_t^H}{\iota}. \tag{19}$$

The change in the real units of aggregate housing stock in the sector is given by $H_t = IH_t + (1-\delta_H)H_{t-1}$, where $\delta_H > 0$ is depreciation of housing stock. Given this, and further factoring in the default scenario, let $H_t = \int_0^1 H_{ht} dh$, when housing demand equals housing supply, we can then write the change in the aggregate housing stock value as:

$$P_t^H \Delta H_t = P_t^H [H_t - (1 - \delta_H - \varphi \varkappa_{t-1}) H_{t-1}]. \tag{20}$$

which depends not only on the depreciation rate, but also the net amount taken by the commercial bank as collaterals (in the event of defaults).

2.4 Capital good producer

There is a capital good producer, collectively owned by the private individuals, who buys gross amounts, I_t^Y and I_t^H, of final good from the retailer in each period to produce capital goods, K_t^Y and K_t^H, which are then rented to the IG firms (at a price, P_t^{KY}) and housing supplier (at a price, P_t^{KH}) respectively. Aggregate capital goods for the two types, K_{t+1}^j,

$j = Y, H$, therefore accumulate as:

$$K_{t+1}^{j} = Z_t^K \left[I_t^j - \frac{\Theta_j}{2} (\frac{K_{t+1}^j}{K_t^j} - 1)^2 K_t^j \right] + (1 - \delta^{Kj}) K_t^j, \tag{21}$$

where $\delta^{KY}, \delta^{KH} \geq 0$ are the constant depreciation rates, $\Theta_Y, \Theta_H \geq 0$ are the standard capital adjustment costs. To better match the model to data, we also introduce stochastic shocks to capital adjustments (assumed to be common for all capital goods, as in Liu and Ou, 2020), governed by the standard AR(1) process, where $Z_t^K = (Z_0^K)^{1-\rho_K} (Z_{t-1}^K)^{\rho_K} \exp(v_t^K)$, where $Z_0^K = 1$, $\rho_K \in (0, 1)$ is the associated AR coefficient, and v_t^K the zero-mean error term with a constant variance (σ_K^2).

Faced with a period-specific real profits function, Π_t^K / P_t, the capital good producer chooses the level of the capital goods for each type K_{t+1}^j, $j = Y, H$, taking rental prices (P_t^{KH}, P_t^{KY}) and the existing stock as given, so as to maximize the lifetime discounted value of profits:[7]

$$\{K_{t+s+1}^Y, K_{t+s+1}^H\}_{s=0}^{\infty} = \arg\max \sum_{s=0}^{\infty} \mathbb{E}_t [\beta^s \lambda_{t+s} (\frac{\Pi_{t+s+1}^K}{P_{t+s}})],$$

subject to (21), which yields for K_{t+1}^j, $j = Y, H$:

$$\mathbb{E}_t \frac{P_{t+1}^{Kj}}{P_{t+1}} = \left[\frac{1}{Z_t^K} + \Theta_j (\frac{K_{t+1}^j}{K_t^j} - 1) \right] (\frac{1 + i_t^D}{1 + \pi_{t+1}}) - \frac{(1 - \delta^{Kj})}{Z_{t+1}^K} - \frac{\Theta_j}{2} \left[(\frac{K_{t+2}^j}{K_{t+1}^j})^2 - 1 \right]. \tag{22}$$

2.5 Commercial Bank

There is a representative commercial bank collectively owned by the individuals. As in studies such as Ravenna and Walsh (2006), Tayler and Zilberman (2016), the IG firms borrow to pay the workers' wages in advance. Let L_{it} be the amount borrowed by firm i, the financing constraint is then $L_{it} = P_t w_t N_{it}$. In return, the commercial bank requires the IG

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[7] The CG producer is assumed to value future profits according to the household's intertemporal marginal rate of substitution in consumption. As such, we have the same discount factor and shadow prices, λ_{t+s}, to those of the household problem.

firm to use the housing units of its owner collaterals, hence giving a collateral constraint of

$$(1+i_t^L)L_{it} = \varkappa \mathbb{E}_t P_{t+1}^H H_{it}, \tag{23}$$

where $(1+i_t^L)$ is the gross lending rate. $\varkappa \in (0,1)$ is the loan-to-value (LTV) ratio. At the end period, there is an exogenous probability of default, $\varphi \in (0,1)$, in which case the bank then seizes the collateral. In the context of China, unlike the developed economies-based studies of Rubio and Carrasco-Gallego (2014), Rubio and Yang (2017), we treat the LTV ratio as fixed, and let the direct setting of LPR, i_t^L, to be a *pseudo*-macroprudential regulatory/policy tool.[8]

In each period, the commercial bank expects to break even from its lending activities such that the expected income from loans equals to the total costs of financing associated with deposits, D_t, and net liquidity injections from the Central Bank, J_t^{CB}, both redeemed/repaid at the end of the period at the total gross value, $(1+i_t^D)(D_t + L_t^{CB})$. Let $L_t = \int_0^1 L_{it} di$ and $H_t = \int_0^1 H_{it} di$, these give $(1-\varphi_t)(1+i_t^L)L_t + \varphi_t \varkappa_t \mathbb{E}_t P_{t+1}^H H_t = (1+i_t^D)(D_t + J_t^{CB})$, or equivalently, using (23),

$$\frac{(1+i_t^L)}{(1+i_t^D)} = \frac{(D_t + J_t^{CB})}{L_t}, \tag{24}$$

which implies that the net interest spread between i_t^L and i_t^D will reflect the (inverse of) optimal asset-to-liability ratio of the Commercial Bank in its balance sheet. Note that, in the case of China, the LPR is indeed higher than the average deposit rate. As such, with LPR, i_t^L, being announced by the Central Bank, and the deposit rate being demand-driven, the Commercial Bank would adjust its asset-liability ratio in each period to break even. Lastly, as required by law (reserve requirement ratio), the commercial bank holds reserves, R_t, at the Central Bank (assumed to pay no interest), which is a fixed fraction of the deposits

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[8] This also allows us to overcome the issues observed in the aforementioned studies, where the LTV ratio in (23) has no effect on the dynamics of the economy (due to the collateral constraint being always binding; hence from the bank's perspective its lending activities are essentially risk-free despite the repayment uncertainty).

taken, $R_t = \mu D_t$, $\mu \in (0, 1)$. The commercial bank's balance sheet is given by:

$$L_t + R_t = D_t + J_t^{CB}, \text{ or equivalently, } L_t = (1 - \mu) D_t + J_t^{CB}, \tag{25}$$

where J_t^{CB} is a net flow term that captures any borrowing from the Central Bank.

2.6 Government and Central Banking

To concentrate on Central Banking policies but allow for policy spaces/rooms to support the subsequent roll-out of CBDC, a simple fiscal policy framework is specified. In each period, the government collects lump-sum tax from individuals ($T_t = \int_0^1 T_{ht} dh$), and issues one-period bonds, which are held by individuals and the Central Bank, $B_t^D = B_t^{HD} + B_t^{CD}$. Following Smets and Wouters (2003), a source of exogenous fiscal policy shock is originated from government expenditure, which follows an AR(1) process, $G_t = (G_0)^{1-\rho_G} (G_{t-1})^{\rho_G} \exp(v_t^G)$, where $G_0 > 0$, $\rho_G \in (0, 1)$, and v_t^G are the persistence, and normally distributed random shock with constant variance (σ_G^2). The period-specific fiscal budgetary constraint is therefore:

$$B_t^D - (1 + i_{t-1}^B) B_{t-1}^D = P_t (G_t - T_t) + J_t^G, \tag{26}$$

where J_t^G is a net (nominal) transfer made to the Central Bank (although it is treated as zero in the benchmark model, as seen later, this gives the corresponding additional 'assets' in the balance sheet of the Central Bank after the CBDC is rolled out, i.e. the expansion in the Central Bank liability due to CBDC is effectively financed by a one-off additional bond issuance by the government).

For the Central Bank, the period-specific balanced sheet is represented by:

$$B_t^{CD} + J_t^{CB} + J_t^G = M_t^F + R_t. \tag{27}$$

Except for when it is used to facilitate the roll-out of CBDC (to be discussed later), we assume the Central Bank to keep its real holding of domestic government bonds constant ($b_0^{CD} = B_t^{CD}/P_t$), implying that any change in the total stock of real government bonds would be due to the change in private bond-holdings.

For the Central Banking policies, prior to the introduction of CBDC, we focus on two policy tools. First, as a Chinese counterpart to conventional monetary policy, following Chang et al. (2019) we assume the Central Bank to use a broad money supply (M2) growth rule. Given that in our model M2 corresponds to $m_t^F + d_t$ (in real terms), denoting $\phi_t = (m_t^F + d_t)/(m_{t-1}^F + d_{t-1})$, we have:

$$\phi_t = \tilde{\phi}(\frac{1+\pi_t}{1+\pi^T})^{\nu_1^m}(\frac{GDP_t}{\overline{GDP}})^{\nu_2^m}\varepsilon_t^{\phi}, \tag{28}$$

where $\nu_1^m, \nu_2^m \in \mathbb{R}$, π^T is the inflation target, $\overline{GDP} = \tilde{Y} + \frac{\tilde{P}^H}{\tilde{P}}\tilde{I}^H$ is the steady-state level of GDP (defined in the tradition of Iacoviello and Neri, 2010), and ε_t^{ϕ} denotes a monetary policy shock governed by AR(1) process, $\varepsilon_t^{\phi} = (\varepsilon_0^{\phi})^{1-\rho_\phi}(\varepsilon_{t-1}^{\phi})^{\rho_\phi}\exp(v_t^{\phi})$, where $\varepsilon_0^{\phi} = 1$, $\rho_\phi \in (0,1)$, and v_t^{ϕ} the zero-mean error term with a constant variance (σ_ϕ^2).

In addition, as a novel feature we also attempt to model the LPR-setting regime post-August 2019, where the Central Bank is assumed to directly set its LPR reference rate, i_t^L, in accordance to:

$$1 + i_t^L = (1 + \tilde{i}^L)\left(\frac{l_t}{l_{t-1}}\right)^{\nu_1}\varepsilon_t^L, \tag{29}$$

where $\nu_1 \geq 0$, and $\tilde{i}^L$ is the steady-state value of the LPR reference rate. ε_t^L is a mean-one stochastic policy shock governed by the standard AR(1) process, where $\varepsilon_t^L = (\varepsilon_0^L,)^{1-\rho_L}(\varepsilon_{t-1}^L)^{\rho_L}\exp(v_t^L)$, where $\rho_L \in (0,1)$ is the AR(1) coefficient, and v_t^L is the zero-mean error term with a constant variance (σ_L^2). Given its pseudo-macroprudential policy nature, the baseline specification for LPR is consistent with Rubio and Carrasco-Gallego (2014), Rubio and Yang (2017), as well as in line with China's real estate market-focused macroprudential regime (Wang and Sun, 2013).

3 Equilibrium: Pre- and Post-CBDC

A symmetric equilibrium in this economy is when the individuals $h \in (0,1)$ make the same choices ($m_t^F = m_{ht}^F$, $m_t^B = m_{ht}^F$, $m_t^{CD} = m_{ht}^{CD}$, $C_t = C_{ht}$, $N_t = N_{ht}$, $\xi_t = \xi_{ht}$, $H_t = H_{ht}$, $B_t^{HD} = B_{ht}^{HD}$, $D_t = D_{ht}$), hence leading to the same ratios ($\chi_t^B = \chi_{ht}^B$) and velocity ($\upsilon_{ht}^F = \upsilon_t^F$), the same paper currency transaction cost ($s_t^F = s_{ht}^F$) and PDC-access cost ($f_t^B = f_{ht}^B$). All domestic IG firms $i \in (0,1)$ make the same input choice decisions ($K_t^Y = K_{it}^Y$, $N_t = N_{it}$), and hence the same IG output and prices across firms.

Further, the final goods market-clearing condition ($Y_t = C_t + I_t^K + G_t$), when adjusted for the housing market, allows us to state a definition of GDP:

$$GDP_t = C_t + \frac{\tilde{P}^H}{\tilde{P}} I_t^H + I_t^K + G_t, \tag{30}$$

which follows Davis and Heathcote (2005) and Iacoviello and Neri (2010), in that housing investment is adjusted by the steady-state house prices, so that any short-run fluctuation in the real house prices do not dramatically affect GDP growth.

In real terms, the government bonds market-clearing conditions is given by $b_t^D = b_t^{HD} + b_0^{CD}$, where $b_t^{HD} = B_t^{HD}/P_t$ is the real value of households' bond-holdings. The cash, deposit, housing, and loan markets clear, which means individuals' demands are met by supplies in their respective sectors. The labor market and the domestic IG market also clear, which by Walras Law, means the PDC market also clears.

As summarized in Appendix A, in the pre-CBDC world, a *dynamic general equilibrium* in the benchmark model economy is characterized by the price/rate sequences $\{w_t, P_t, P_t^H, P_t^{KH}, P_t^{KY}, i_t^D, i_t^B, P_t^B, i_t^L, q_t\}$, ratios $\{\xi_t, \Upsilon_{Bt}, \chi_t^B\}$, as well as real quantities $\{C_t, N_t, Y_t, b_t^{HD}, b_t^{CD}, b_t^D, d_t, m_t^B, m_t^F, l_t, H_t, K_t^H, K_t^Y\}$ and costs $\{s_t^F, f_t^B, mc_t\}$, such that, taking price/rate sequences, inflation rates (π_t, π_t^H), growth rates ($e_t/e_{t-1} = 1 + g_e$; $A_t/A_{t-1} = 1 + g_A$), and the stochastic shocks as given: (i) all individuals maximize utility; (ii) all IG firms maximize profits; (iii) the representative commercial bank and retailer break even; (iv) the Central Bank's and the government's flow-of-funds and budget constraints are satisfied; (v) all markets clear.

Next, to study the responses of the economy to shocks, we log-linearize the model around a nonstochastic, zero-inflation s*teady state equilibrium with balanced growth.* Specifically, let g_A be the balanced growth rate, and suppose $g_e = 0$, the steady state equilibrium with balanced growth is when all real quantities are growing at $1 + g_A$; the economy is free from stochastic shocks, the ratios, velocity, and prices/rates are constant. The log-linearized model is summarized in Appendix B.

As discussed in Section 1, there is a burgeoning literature on CBDC debating on the merits (and demerits) of the different designs of a CBDC. Notwithstanding the generally agreed consensus characteristics of it being digital, a liability of the Central Bank, and universally accessible to all, there remain outstanding issues in terms of the optimal design of a CBDC, notably on whether CBDC should be: (i) token- or account-based; and (ii) the interest rate/return of CBDC, hence also how much it is suppose to be traded (Meaning et al., 2018). In practice, DCEP is based on an account-based design due to the requirement of individual registration[9]. Issue (ii) is the well documented debate on paying CBDC with negative interest rate to break the zero lower bound problem (i.e., Agarwal and Kimball, 2015; Rogoff, 2016), which indirectly calls for the possibility of having CBDC trading below par compared to other Central Bank liabilities. In addressing (ii), for the full model with CBDC, we set the CBDC interest rate, i_t^{CD}, to be at a negative spread of the deposit rate, i_t^{CD}, therefore allowing for a gross CBDC interest rate, $1 + \tilde{\imath}^{CD} < 1$. Specifically, we set a baseline CBDC policy rule of $1 + i_t^{CD} = (1 + i_t^D) - 0.08$.

For the roll-out of CBDC, the Central Bank is assumed to issue an initial fixed quantity, M_0^{CD} to the individuals, with the liability (in Central Bank's balance sheet) met by an equivalent amount transferred from the government, financed by one-off issuance of new bonds. Mathematically, this means the steady-state value of real quantities of CDBD and

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[9] While individual accounts under the current DCEP experiment are tied to their commercial bank accounts, any Digital Yuan issuance is backed by an equivalent amount of reserves made with the PBOC, i.e. equivalent to centralized depository with the Central Bank. As such, we adopt a simplified model specification in the post-CBDC world where CBDC is directly issued by the Central Bank.

government bonds would differ as follows: $\tilde{m}^{CD} = 0$ in the benchmark model to $\tilde{m}_i^{CD} = M_0^{CD}/\tilde{P}$ in the post-CBDC world; $\tilde{b}^D$ in the benchmark model to $\tilde{b}_i^D = \tilde{b}^D + M_0^{CD}/\tilde{P}$; $\tilde{b}^{CD}$ in the benchmark model to $\tilde{b}_i^{CD} = \tilde{b}^{CD} + M_0^{CD}/\tilde{P}$. Due to the share of PDC in individuals' portfolio of currencies having become smaller ($\tilde{\chi}^B$), the steady-state value of PDC-access cost, $\tilde{f}^B$ would permanently increase to $\tilde{f}_i^B > \tilde{f}^B$, which would then affect the steady-state values of cash ($\tilde{m}^F$), PDC ($\tilde{m}^B$), and consequently other variables.

In terms of the dynamic system, on top of (4)-(9), an additional first-order condition is derived, which in a symmetric equilibrium gives the real demand for CBDC:

$$m_t^{CD} = \left\{ \frac{\eta_M w_t}{\eta_N (N_{ht})^{\varsigma_N}} + \left[\zeta_1 f_t^B m_t^B - \frac{\eta_M w_t}{\eta_N (N_{ht})^{\varsigma_N}} \right] \chi_t^B \right\} \frac{(1 + i_t^D)}{(i_t^D - i_t^{CD})} - m_t^F, \tag{31}$$

where there is a direct trade-off to cash, and inversely dependent on the interest spread between deposit and CBDC. Assuming that the Central Bank always stands ready to meet all CBDC demand, CBDC market will be in equilibrium, with its period-specific balance sheet equals:

$$B_t^{CD} + J_t^{CB} + J_t^G = M_t^F + M_t^{CD} + R_t. \tag{32}$$

4 Calibration and Estimation

To study the role, interaction, and optimality of the three central banking policies in China (money supply growth rule, LPR-setting, and CBDC policy rule), our empirical strategy is as follow. First, for the pre-CBDC benchmark model we estimate it using the Bayesian method in the tradition of Smets and Wouters (2003). Specifically, taking advantage of the availability of bitcoin prices since late-2013 (which is used as a proxy measure for PDC price), the model is estimated using a mixed frequency technique based on actual data of 9 detrended time series adjusted to monthly frequency, covering the period of 2013M11 to 2019M12 ($T = 74$). Three series are originally in monthly frequency (housing price index, CPI inflation rate, bitcoin prices), whereas five macroeconomic series (real per capita GDP, real per capita consumption, real per capita private investment, new housing production, total labor hours) are converted to monthly series using the quadratic average method. For the ninth, due to LPR being a relatively new concept, we estimate/construct the series based on its definition: a measure of the most preferential market lending rate offered by the large commercial banks. Specifically, starting from the monthly series of market-based REPO rate of China commercial banks surveyed by Bloomberg, we add to the series the average interest spreads of the 4 largest commercial banks of China (Agriculture Bank of China, China Construction Bank, Industrial & Commercial Bank of China, Bank of China) to yield a market-based historical LPR series that approximates its definition.

The number of series is chosen to be one less of the number of structural shocks (10) to avoid stochastic singularity, and the additional degree of freedom allows us to more easily solve the model while estimating 29 dynamic parameters [ς_N, η_M, ϱ, ϖ, Θ_Y, Θ_H, ν_1, ν_1^m, ν_2^m, 10 AR(1) parameters, and 10 standard deviation parameters]. The remaining parameters are calibrated to match the initial steady-state values of key macroeconomic ratios to the long-run state of China: consumption-to-GDP ratio of 52%, non-residential investment ratio of 32%, residential investment ratio of 3%, government spending ratio of 15%, cash-to-GDP ratio of 13%, and bitcoin market capitalization-to-GDP ratio of 0.3%. After the benchmark model is estimated and analyzed, the Bayesian-estimated posterior estimates are retained, which together with the other calibrated parameters, are used in the parameterization and solving of the expanded/'full' post-CBDC world model.

The calibrated parameters are summarized in Table 2. The discount factor, $\beta = 0.998$, is consistent with a monthly deposit return of 0.23%, or equivalently, 2.8% per annum. In line with Bayesian estimation-based models for China (Minetti and Peng, 2018; Liu and Ou, 2020), we set a fairly small $\eta_N = 1.0$ for labor weight, and try to estimate the Frisch elasticity using data. The housing preference parameter is set at $\eta_H = 0.6$, which together with monthly depreciation rates of $\delta^{KY} = 0.01$, $\delta^{KH} = 0.0133$, $\delta_H = 0.005$ (in quarterly context, these correspond to 3.0%, 4.0%, 0.015%, as in Minetti et al., 2019), generate steady-state residential investment-to-GDP ratio of 3%. For the paper currency transaction cost parameters, we set $A_F = 0.01$ and $B_F = 0.25$ so as to yield a steady-state velocity of money at 1.16, in line with the value of China. On the other hand, for the PDC-holding cost parameter, $\zeta_1 = 30$ is set so as to target a 0.3% bitcoin market capitalisation-to-GDP ratio.

Next, the elasticity of IG with respect to capital stock, α, is set a rather standard value of 0.35. For the elasticity of substitution between IG, the average profit margin of Chinese firms is 0.17, which yields a gross mark-up of 1.205, implying $\theta = 5.9$. The elasticity of housing production with respect to capital stock, $\iota = 0.2$, is set following Liu and Ou (2020). The loan default probability, $\varphi = 0.0292$ is set in accordance to those reported by the China Banking and Insurance Regulatory Commission. The reserve requirement ratio, μ, is set at 0.125, which approximates the average reported by the People's Bank of China over the past 5 years. Similarly, the LTV ratio, $\varkappa = 0.6$ is set, which is slightly below the usual maximal LTV ratio of 0.8 but in line with the average observed in the corporate sector in China.

4.1 Estimated parameters

For the Bayesian-estimated dynamic parameters, Table 3 reports the prior and posterior distributional forms, means, and standard deviations. The priors on these parameters are chosen so that they are in line with existing Bayesian estimation-based DSGE studies for China featuring housing market (Minetti et al., 2019; Liu and Ou, 2020) and harmonized across different shocks. Moreover, the choices of prior distributions take into consideration the parameters' domain and prior means, as in the existing literature.

First, the prior mean of the inverse of the Frisch elasticity of labor supply, ς_N, is set at 1.5, in line with meta analysis of Chetty et al. (2011). The prior for the money-holding utility weight, η_M, is set at 0.025, following Agenor et al. (2014). The priors of the two parameters in the NKPC ($\varpi = 0.67$, $\varrho = 0.5$) follow Liu and Ou (2020), which uses the same Calvo-Yun pricing set-up. In the literature, it is conventional to set the prior mean of the capital adjustment cost parameters (Θ_Y, Θ_H) to be a large value, such as the 100 reported in Hristov and Hülsewig (2017). However, in Minetti et al. (2019), the estimated values are merely 3.02 and 3.75. Similarly, in the US based study of Iacoviello and Neri (2010), the estimated parameters are 11.5 and 6.99. For starting priors, we therefore set $\Theta_Y = \Theta_H = 10$ and let data 'speaks'. Next, we deal with the M2 growth rule and LPR policy function, both of which without precedents in the Bayesian estimation. For the former, we set the priors for ν_1^m and ν_2^m to follow the calibration of Chang et al. (2019), hence $\nu_1^m = -0.65$ and $\nu_2^m = 0.3$. For the latter, we set $\nu_1 = 0.5$ in the absence of reference and use a loose standard deviation to let the data 'speaks' again.

As in Hristov and Hülsewig (2017), we give relatively large prior variance to structural parameters so that the kurtosis of posterior distributions is not heavily influenced by the prior means: the data can therefore "speak for themselves". Similarly, for the shock persistence and standard deviation parameters, our choices of prior means are consistent with the existing Bayesian DSGE literature, such as Christiano et al. (2005), Smets and Wouters (2003), Geweke (2005). Specifically, we assume Beta distribution with 0.5 mean and 0.2 standard deviation for the AR(1) parameters, and inverse-gamma distribution with 0.1 mean and 2.0 standard deviation for the standard deviation parameters.

The estimated posterior mean for the inverse Frisch elasticity, ς_N, is 3.53, which is even larger than the 2.0 set by Chang et al. (2019) but within an acceptable range. The estimated posterior mean for the money-utility weight, $\eta_M = 0.004$, which has perhaps accounted for the fact that there are different types of money in this model. The two Calvo-Yun NKPC parameters, ϱ and ϖ, are estimated at 0.30 and 0.24, in line with Liu and Ou (2020). The two capital adjustment cost parameters are estimated at $\Theta_Y = 18.7$ and $\Theta_H = 6.5$, which when compared to Minetti et al. (2019), are obviously much larger but within range of the estimates usually obtained in the aforementioned Bayesian DSGE literature, including Iacoviello and Neri (2010). Alternatively, the estimated value may imply high adjustement cost for the two types of capital on a monthly frequency. For the M2 growth rule, the posterior means are estimated at $\nu_1^m = -0.72$ and $\nu_2^m = 0.25$. These two monetary policy mandates are in line with the calibrated values used in Chang et al. (2019). Lastly, for the elasticity of LPR with respect to loan growth, ν_1, the estimated posterior mean is 0.004, which is small enough to suggest that there may be a limited relationship between the variation in loan prime rate and total loan growth in the Chinese economy.

5 Analysis

First, we examine the estimated results for both variance decomposition and impulse response analysis of the benchmark model without CBDC. Next, to examine "how things would change" post-CBDC implementation, we then analyze the variance decomposition and impulse responses of the post-CBDC world. Specifically, this first involves attempt to identify common cyclicality patterns across macroeconomic variables in our benchmark economy, including their responsiveness to their different shocks. Then, with the introduction of CBDC, we see how the cyclicality and persistence of adjustments of the key macroeconomic variables to economic shocks would differ.

The second part then involves the search for an optimal design of the new monetary policy regime. Specifically, we search for welfare-optimal policy designs for the three central banking policies considered, based on an objective of maximizing the aggregate version of (1), as in a welfare function of:

$$\max W_t = \mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \left[\begin{array}{c} \ln C_{t+s} + \eta_H \ln H_{t+s} \\ +\eta_M \ln(m_{t+s}) - \eta_N \frac{(N_{t+s})^{1+\varsigma_N}}{1+\varsigma_N}. \end{array} \right] \tag{33}$$

To minimize computational complexity, we approach the welfare optimality search sequentially. Specifically, we first examine for a welfare-optimal design for the LPR policy function, (29)—of the three, the central banking policy with the least existing reference we can refer to. However, given that the baseline policy functional form for LPR-setting appears to be weak, we also examine the responsiveness of LPR with respect to other asset markets too (in a welfare-optimal context), so as to identify an optimal design for LPR-setting. After that, we search for welfare-optimal policy mandates—in conventional inflation and output stabilization mandates—for both traditional monetary policy (M2 supply growth rule) and the CBDC policy. As mentioned, in the baseline, we simply set CBDC return to be a constant discount of the private deposit rate, $1 + i_t^{CD} = (1 + i_t^D) - 0.08$. In searching for a welfare-optimal design of a potential CBDC policy rule, we consider a "price-targeting benchmark rule" suggested by Bordo and Levin (2017), as in:

$$1 + i_t^{CD} = (1 + i_{Policy}^{CD})(\frac{1 + \pi_t}{1 + \pi^T})^{\kappa_1}(\frac{GDP_t}{\overline{GDP}})^{\kappa_2}, \tag{34}$$

where $\kappa_1, \kappa_2 \in \mathbb{R}$, and $i_{Policy}^{CD} = \tilde{\imath}^{CD} \in \mathbb{R}$ is a CBDC benchmark rate.

5.1 Variance Decomposition and Impulse Responses

Table 4 and Table 5 report the unconditional variance decomposition analysis of all the key model variables for the benchmark model and post-CBDC world respectively. First, consistent with most China-focused DSGE models, productivity shock is observed to be the primary driver, contributing to over 40 percent of the variations in GDP, consumption, labor supply, and cash. This is despite of the shortened frequency (monthly) applied in our Bayesian estimation. After that, preference shock and the cash velocity-related shock are the most significant drivers of economic volatility. The former is consistent with the characteristics of most DSGE models, and preference shock is observed to be the one of the top three drivers of variations for all but five of the variables presented in Table 4. By design, sources of monetary impulses are expected to play a significant role in the model, and this is reflected in the latter. Nevertheless, between the two sources, it appears that most of the variations in paper monies are captured by the demand-side shock tied to its velocity, instead of the structural shock within the M2 supply growth rule. Intuitively, we believe that this reflects the relative unknown of the drivers of money velocity in China, where a geographically dispersed economy with significant rural sectors means any residual volatility related to money is likely to be captured by this structural shock, instead of the quantity-based monetary policy function (within which the price and output stabilization ought to have accounted for most variations).

In terms of the credit sector, consistent with studies such as Minetti et al. (2019), Liu and Ou (2020), it appears that variations in credit/loan in the Chinese economy is predominantly driven by the housing market, as 56.86 percent of the variations in loans are driven by the structural shock in housing production. The PDC price, although being specified as a source of structural shock, is found to be mainly contained within its own market, with non-existent (little) spillover to the production sector and credit (cash and inflation). Nevertheless, within the stylized context of our model, portfolio reallocation of financial assets by households means the variation in PDC prices accounts for the bulk of the variation in government bonds held by individuals. As such, while PDC is unlikely to pose a threat to financial stability in China, it may distort the appetite for domestic government bonds, especially in periods when PDC are yielding abnormally large returns. This perhaps partly explains the tough crackdown on cryptocurrency within China in recent years.

Based on this benchmark set of estimation, we then consider the results in Table 5, which illustrates the model economy post-implementation of CBDC. Post-implementation of CBDC, we see that the dominant role of productivity shock remains, followed by preference shock and the cash velocity-related shock. While most qualitative features remain, a couple of significant differences are observed. First, the influence of the PDC price shock is significantly reduced compared to the benchmark case, notably the distortionary impact on domestic government bond demand has diminished. Second, productivity shock appears to account for more variation in the aggregate inflation rate now, at the expense of shock associated with loan prime rate. While this could merely reflect computational anomalies, these do suggest that the introduction of CBDC could have a portfolio reallocation effect that improves domestic stability, as it reduces the effect of PDC price and loan rate on key macroeconomic variables.

In terms of the two new variables in the post-CBDC world, we see that variation in CBDC quantity would be primarily driven by PDC price shock, followed by cash velocity-related shock, preference shock, and LPR-related shock. In contrast, for the CBDC interest rate, the primary drivers are cash velocity-related shock and preference shock. Given that the eventual CBDC regime could take a vastly different form, these results should be interpreted with caution. Nevertheless, these results suggest that variations in the PDC market, especially if these cryptocurrencies do have a reasonable degree of acceptance as means of payments, would have a significant effect on the private holdings of CBDC. Indeed, in a regime where cash will co-exist with CBDC (as in China), then the designated return for CBDC is potentially dependent on the velocity of cash circulation.

Figures 1-4 compare the impulse response functions (IRFs) of key variables to four shocks between the benchmark model and the post-CBDC world. Given its dominant role, Figure 1 illustrates the IRFs to one standard-deviation productivity shock. Qualitatively, the IRFs are largely within expectation, where GDP, consumption, investments are pro-cyclical. These are the same for the demand for cash, loan, PDC, deposits, as well as the prices (p_t^H, i_t^D, i_t^L), which are all procyclical to productivity shock. While the cyclicality remains largely the same in the post-CBDC world, it appears that for some variables (notably the financial assets), such as the cash (m_t^F), deposits (d_t), and PDC (m_t^B), the presence of CBDC amplifies the effects of productivity shock, though there are no noticeable difference in the persistence of adjustment path (except for m_t^B). Next, Figure 2 compares the IRFs of variables' responses to a one standard-deviation housing productivity shock. Again, in the post-CBDC world, the responses of both key macroeconomic and monetary asset variables to the specific shock appear to be amplified, with short-term fluctuations to be much more volatile. In essence, the presence of CBDC would provide a source of amplification, leading to more significant cyclicality of major macroeconomic variables. Indeed, this is the same with preference shock, for which the IRFs are not presented to save space.

While the introduction of CBDC appears to deepen the procyclical nature of variables to real business cycle shocks, the IRFs to a one standard-deviation shock in cash velocity-related transaction cost (presented in Figure 3) do not show noticeable difference between the benchmark model and the post-CBDC world. While GDP and investments appear to be counter-cyclical to cash velocity shock, the presence of CBDC does not lead to much difference in the amplification or persistence of adjustment path. Indeed, when we examine the IRFs of variables in response to a one standard-deviation shock to LPR in Figure 4, the opposite is observed. Specifically, in the case of a stochastic shock to LPR, the post-shock transition path of variables appear to be less volatile in the post-CBDC world. Indeed, the transition path of selected variables also appears to be less persistence, notably for loan, inflation, and housing price. In addition, we also observe a change in the direction of movement for GDP and consumption after the introduction of CBDC. In summary, despite the introduction of CBDC likely to deepen the procyclicality of variables in response to real business cycle shocks, it appears to not worsen those of monetary impulses. The LPR policy-setting may have merits in migitating this due to its improved stabilization properties in the post-CBDC world. Indeed, in Figure 5, which summarizes the IRFs of CBDC (m_t^{CD}) to all ten shocks in the model economy, we see that CBDC, while largely anti-cyclical to most shocks, is procyclical to a structural shock to LPR-setting (another being inflationary shock). This suggests a potential policy complementarity between LPR and CBDC.

5.2 Optimal Policy Design

Due to its novelty and lack of precedents in the existing literature, we first attempt to pin down a welfare-optimal design for LPR policy function. Using a numerical grid search method, we search for an optimal value of the elasticity with respect to loan growth, ν_1, in (29) that maximizes the welfare function in (33) for both the benchmark model and the post-CBDC world. The results are presented in Table 6. It can be seen that an interior optimal parameter value for ν_1 does not exist in both cases, and this, coupled with the very small value obtained in Bayesian estimation (0.004), suggests that having a LPR policy mandate of targeting loan growth (as if it is a standard macroprudential tool) may be inefficient. Given this, we then attempt to include the growth in various asset markets (in nominal values), which include housing market, capital asset market, and in the case of the post-CBDC world, the growth in CBDC in itself. After numerous experiments, we identify some interior solutions for optimal policy parameters if the policy mandates of LPR-setting were to be directly targeting of potential asset bubbles. Specifically, in the "no CBDC" benchmark model, we find a welfare-optimal design of LPR policy function to be

$$1 + i_t^L = (1 + \tilde{\imath}^L) \left(\frac{P_{t+1}^H H_t}{P_t^H H_{t-1}} \right)^{o_H} \left(\frac{P_{t+1}^K K_t}{P_t^K K_{t-1}} \right)^{o_K} \varepsilon_t^L, \tag{35}$$

where $P_{t+1}^K K_t = P_{t+1}^{KH} K_t^H + P_{t+1}^{KY} K_t^Y \ \forall t$, and the interior optima being $o_H = 0.052$, and $o_K = -0.100$. Likewise, in the post-CBDC world, we have a welfare-optimal design of

$$1 + i_t^L = (1 + \tilde{\imath}^L) \left(\frac{P_{t+1}^H H_t}{P_t^H H_{t-1}} \right)^{o_H} \left(\frac{P_{t+1}^K K_t}{P_t^K K_{t-1}} \right)^{o_K} \left(\frac{m_t^{CD}}{m_{t-1}^{CD}} \right)^{o_{CD}} \varepsilon_t^L, \tag{36}$$

where the interior optima are $o_H = 0.046$, $o_K = -0.108$, and $o_{CD} = 0.461$.

In essence, the welfare-optimal LPR-setting rules of (35) and (36) suggest that, instead of targeting loan growth, a more efficient policy function is for the Central Bank to determine LPR based on housing market stabilization mandate, while reducing loan prime rate when the capital asset market is in a bearish state. Indeed, given that the practicality of LPR-setting involves a survey of panel banks' rates (strictly speaking, PBOC therefore does not directly intervene), a policy-targeting of loan growth will pose a conflicting objective to the commercial banks. As such, an advisory approach that seeks to target the states of housing and capital asset markets will have more practical sense too. Interestingly, in the post-CBDC world, we also identify an interior optimal solution to a policy mandate targeting CBDC growth, o_{CD}. This, coupled with the observations from earlier analysis, reinforces a potential policy complementarity between LPR and CBDC policies.

Having pinned down an optimal policy function for LPR-setting, we then search for an optimal policy design for monetary policies—both the traditional M2 growth rule and a potential CBDC policy rule. When the rate of return to CBDC is first set at a discount to private deposit rate, we see that only the output stabilization mandate yields an interior welfare-optimal value, $\nu_2^m = 0.19$. When we allow for a CBDC policy rule, as in (34), and then implement a computational-intensive joint search of 4 policy parameters $(\nu_1^m, \nu_2^m, \kappa_1, \kappa_2)$, we observe that the traditional money supply growth rule losses its mandate on output and price stabilization. Instead, welfare-optimal policy parameters of $\kappa_1 = 0.932$, $\kappa_2 = 1.732$ are identified for the CBDC policy rule. This suggests that only one form of active monetary policy should be used after the full implementation of CBDC, if both cash and CBDC are existing concurrently in the Chinese economy.

6 Concluding Remarks

In recent years, the financial system in China has witnessed two major policy changes: (i) a LPR reform in 2019; and (ii) a movement towards using CBDC. In preparation for the latter, the Chinese government has also actively discouraged the trading of cryptocurrency. We study the business cycle and financial stability properties of the two central banking policies, as well as the traditional M2 supply growth rule applied in Chang et al. (2019). We develop a DSGE model with cash and digital currency, both being used as payment options by households for consumption. The former is subject to cash velocity-related transaction costs similar to Barrdear and Kumhof (2016). To examine the effects brought about by a full implementation of CBDC, we distinguish between a benchmark model and a "Post-CBDC world", where prior to the implementation of CBDC the households pay digitally using private digital currency (PDC), albeit with a significant holding/access cost due to the direct trading using Chinese Yuan within China being restricted since 2018.

The benchmark model is a Bayesian estimated model for the Chinese economy. Based on the posterior means estimated, the model is then calibrated and solved for a stylized post-CBDC world, where quantities of CBDC would then become households' choice of monetary assets too (determined from households' optimization problem). Inspecting the IRFs, we find that, following the introduction of CBDC, macroeconomic variables that are procyclical to real business cycle shocks would display greater procyclicality, leading to an increase in short-term volatility. However, we also find a potential LPR-setting policy to exhibit an improved stabilization property in the post-CBDC world, therefore some degree of policy complementarity with CBDC. Indeed, we uncover an optimal design of LPR policy function, which targets more specifically housing and capital asset markets, as well as the growth in CBDC. This suggests a potential interaction of these two seemingly unrelated central banking policies in the financial stability agenda of the Chinese economy going forward.

For future research, note that the various experiments with DCEP remain in their infancy in China. Given the various potential designs that are available for CBDC, the eventual economy-wide implementation of Digital Yuan is likely to be quite different from our stylized model. For instance, it might be that PBOC's intention with DCEP is one targeting towards replacing the segmented digital payment system in China, where Digital Yuan may turn out to be just a centralized payment platform in place of the Alipay, WeChat Pay, etc. in China. In this instance, a more experimental design based study will be warranted. In addition, our study also cannot comment much about whether a unique exchange rate system between cash and CBDC should be implemented. This, along with other CBDC considerations, notably the other systemic risks associated with mantaining a DLT system for an economy with nearly 1.4 billion population, are potential topics.

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Table 1: Salient characteristics of the three different currencies and one bank deposit in the model

	Cash M_t^F	PDC M_t^B	CBDC M_t^{CD}	Deposit D_t
Monetary transaction cost (velocity-based, including all opportunity costs associated with holding & exchanging cash, etc.)	s_t^F	0	0	0
Cost of access & holding (include regulatory concealment costs, etc.)	0	f_t^B	0	0
Interest-bearing	No	No, but through change in market prices, $\frac{E_t P_{t+1}^B}{P_t^B}$	$i_t^{CD} \in \mathbb{R} < i_t^D$	$i_t^D \geq 0$
Payment instrument	Yes	Yes	Yes	No
Issuer/ Liability of:	Central Bank	Exogenous to the model	Central Bank	Commercial Bank

Table 2: Benchmark Calibrated Parameter Values

Parameter	Definition	Value
	Households and Money	
β	Household's discount factor	0.998
η_H	Housing preference	0.6
η_N	Disutility of labour	1
A_F	Paper currency transaction cost, 1	0.0098
B_F	Paper currency transaction cost, 2	0.25
ζ_1	PDC holding cost elasticity	30
	Production, Housing, and Capital	
δ^{KY}	Normal capital depreciation rate	0.01
δ^{KH}	Housing capital depreciation rate	0.0133
δ_H	House depreciation rate	0.005
α	Capital Share	0.35
θ	Elasticity of substitution, IG	5.9
ι	Housing production elasticity	0.2
	Banking and Policies	
φ	Probablity of default rate	0.0292
$\varkappa$	Loan-to-value (LTV) ratio	0.6
μ	Reserve requirement ratio	0.125
κ_1	CBDC policy response to inflation	0.5
κ_2	CBDC policy response to GDP	0.5

Table 3: Summary Statistics for Prior and Posterior Distribution of Parameters

	Prior distribution			Posterior	
Parameter	Distribution	Mean	Std	Mean	Std
Structural Parameters					
ς_N	Gamma	1.5	0.5	3.529137	0.52454
η_M	Gamma	0.025	0.001	0.003847	0.000883
ϱ	Beta	0.5	0.2	0.304762	0.167374
ϖ	Beta	0.67	0.10	0.236015	0.044193
Θ_Y	Gamma	10	2.5	18.71734	1.142314
Θ_H	Gamma	10	2.5	6.506278	1.583897
ν_1	Normal	0.5	0.1	0.004374	0.004277
ν_1^m	Normal	-0.65	0.1	-0.7202	0.090581
ν_2^m	Normal	0.30	0.1	0.248963	0.092173
Shock Persistence Parameters					
ρ_s	Beta	0.5	0.2	0.967016	0.007899
ρ_B	Beta	0.5	0.2	0.390274	0.088563
ρ_{ZH}	Beta	0.5	0.2	0.744193	0.028808
ρ_{ZY}	Beta	0.5	0.2	0.991275	0.003793
ρ_π	Beta	0.5	0.2	0.867952	0.027395
ρ_ϕ	Beta	0.5	0.2	0.339692	0.149349
ρ_L	Beta	0.5	0.2	0.497857	0.065386
ρ_G	Beta	0.5	0.2	0.988768	0.013959
ρ_C	Beta	0.5	0.2	0.902584	0.014751
ρ_K	Beta	0.5	0.2	0.96157	0.013557
Shock Standard Deviation Parameters					
$100\sigma_s$	Inv. gamma	0.1	2	0.817824	0.178761
$100\sigma_B$	Inv. gamma	0.1	2	20.3425	1.673694
$100\sigma_{ZH}$	Inv. gamma	0.1	2	1.362452	0.140315
$100\sigma_{ZY}$	Inv. gamma	0.1	2	0.434834	0.035434
$100\sigma_\pi$	Inv. gamma	0.1	2	2.118383	0.55418
$100\sigma_\phi$	Inv. gamma	0.1	2	0.04408	0.014068
$100\sigma_L$	Inv. gamma	0.1	2	0.064201	0.005511
$100\sigma_G$	Inv. gamma	0.1	2	0.96191	0.079755
$100\sigma_C$	Inv. gamma	0.1	2	1.620919	0.167745
$100\sigma_K$	Inv. gamma	0.1	2	0.35165	0.05049

Table 4: Variance Decomposition Analysis - Benchmark model (No CDBC)

	Structural Shocks									
Variables	Paper currency velocity-related	PDC price	Preference shock	Capital investment	Housing production	Final good production	Inflation shock	Gov. spend. shock	M2 growth rule	LPR policy rule
GDP, GDP_t	15.24	0.00	4.28	1.29	0.14	77.59	1.34	0.11	0.00	0.01
Final good, Y_t	16.38	0.00	3.93	1.47	0.00	76.75	1.32	0.13	0.00	0.01
Real wage, w_t	19.82	0.04	5.43	2.50	0.05	9.89	60.90	1.04	0.03	0.30
Consumption, C_t	26.67	0.02	15.44	1.36	0.02	51.92	0.09	4.24	0.00	0.24
Labor supply, N_t	24.35	0.01	14.50	1.04	0.02	43.19	13.48	3.38	0.01	0.03
New housing, IH_t	1.14	0.00	1.57	0.12	96.28	0.79	0.00	0.08	0.00	0.00
Cash, m_t^F	23.17	12.08	13.59	1.20	0.02	45.79	0.08	3.74	0.00	0.35
PDC, m_t^B	0.02	99.93	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00
Total deposits, d_t	64.99	0.02	23.96	0.71	0.72	8.62	0.09	0.19	0.00	0.68
HH gov. bonds, b_t^H	0.98	95.48	2.05	0.10	1.12	0.23	0.01	0.03	0.00	0.00
Inflation rate, π_t	32.20	1.44	33.79	7.30	1.73	13.31	0.04	1.71	1.14	7.35
Housing price, P_t^H	14.07	0.00	20.06	3.94	55.97	5.36	0.02	0.56	0.00	0.02
Investment, FG, I_t^Y	60.23	0.02	28.94	2.09	0.00	6.38	1.25	0.84	0.00	0.25
Invest., Housing, I_t^H	11.15	0.04	46.46	0.55	35.12	5.56	0.02	0.59	0.00	0.51
Deposit/bond rate,$i_t^D = i_t^B$	8.76	0.00	2.14	0.26	4.66	1.15	0.01	0.07	0.00	82.96
Loan rate, i_t^L	0.05	0.00	1.46	0.07	1.11	0.08	0.00	0.01	0.00	97.23
Loan, l_t	14.81	0.00	18.15	4.14	56.86	5.44	0.02	0.57	0.00	0.02
Paper money tran. cost, s_t^F	99.99	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PDC access cost, f_t^B	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Real marginal cost, mc_t	1.17	0.07	1.43	0.28	0.08	0.50	95.94	0.06	0.04	0.43

Table 5: Variance Decomposition Analysis - Post-CBDC World

	Structural Shocks									
Variables	Paper currency velocity-related	PDC price	Preference shock	Capital investment	Housing production	Final good production	Inflation shock	Gov. spend. shock	M2 growth rule	LPR policy rule
GDP, GDP_t	16.60	0.00	4.70	1.31	0.09	75.85	1.29	0.14	0.00	0.00
Final good, Y_t	17.78	0.00	4.36	1.50	0.00	74.92	1.26	0.16	0.00	0.00
Real wage, w_t	20.88	0.00	4.99	2.54	0.01	9.76	60.94	0.87	0.00	0.01
Consumption, C_t	26.14	0.03	13.55	3.08	0.16	51.43	0.45	4.63	0.12	0.41
Labor supply, N_t	26.18	0.00	16.13	1.06	0.01	41.34	12.03	3.23	0.02	0.01
New housing, IH_t	1.18	0.00	1.56	0.16	96.23	0.79	0.00	0.07	0.00	0.00
Cash, m_t^F	23.54	9.01	11.99	3.47	0.24	46.01	0.61	4.35	0.18	0.60
PDC, m_t^B	4.31	86.02	2.85	2.06	0.52	0.06	0.78	0.60	0.28	2.53
Total deposits, d_t	67.01	0.04	22.19	1.26	0.48	7.61	0.67	0.42	0.12	0.20
HH gov. bonds, b_t^H	0.10	5.07	82.72	0.61	10.57	0.67	0.15	0.11	0.00	0.00
Inflation rate, π_t	26.83	0.50	30.71	3.27	0.63	31.60	4.94	0.80	0.62	0.10
Housing price, P_t^H	14.76	0.00	18.74	4.21	56.41	5.24	0.06	0.53	0.01	0.04
Investment, FG, I_t^Y	59.66	0.04	26.68	4.03	0.21	5.79	2.14	0.87	0.16	0.44
Invest., Housing, I_t^H	12.50	0.09	39.66	4.19	34.02	6.16	1.12	0.85	0.35	1.06
Deposit/bond rate,$i_t^D = i_t^B$	8.69	0.00	2.41	0.37	4.88	1.01	0.02	0.10	0.01	82.52
Loan rate, i_t^L	0.16	0.00	1.15	0.03	1.04	0.09	0.01	0.00	0.00	97.51
Loan, l_t	15.00	0.00	17.64	4.50	57.00	5.23	0.03	0.55	0.01	0.04
Paper money tran. cost, s_t^F	99.99	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PDC access cost, f_t^B	0.39	98.76	0.25	0.19	0.04	0.01	0.07	0.06	0.03	0.20
Real marginal cost, mc_t	0.17	0.00	0.34	0.01	0.00	0.60	98.89	0.00	0.00	0.00
CBDC, m_t^{CD}	20.46	31.89	13.30	10.20	2.58	0.53	3.78	2.98	1.35	12.94
CBDC interest rate, i_t^{CD}	40.79	1.81	21.92	17.29	2.27	0.79	6.94	4.98	2.47	0.71

Table 6: Welfare-Optimal Loan Prime Rate (LPR) setting

Loan Prime Rate (LPR) policy function	Benchmark model	Optimal policy parameters	
	Bayesian-estimated policy parameters	Benchmark model No CBDC	Post-CBDC world With CBDC
Baseline functional form:			
Elasticity: Loan Growth	0.004	0.000	0.000
Alternative policy mandates:			
Elasticity: Loan Growth	n.a.	n.a	n.a
Elasticity: Housing market	n.a.	0.052	0.046
Elasticity: Capital asset market	n.a.	-0.100	-0.108
Elasticity: m^{CD}	n.a.	n.a.	0.461

Table 7: Welfare-Optimal Monetary Policy

Money Supply (M2) Growth Rule and CBDC Policy Function

Monetary policy function	Benchmark model	Optimal policy parameters	
	Bayesian-estimated policy parameters	Conditional search	Joint-search of 4 parameters
M2 growth rule			
Elasticity: inflation gap	-0.720	0.000	0.000
Elasticity: output gap	0.249	0.190	0.000
CBDC policy rule			
Baseline form	$i_t^{CD} = i_t^D - 0.08$	$i_t^{CD} = i_t^D - 0.08$	
Elasticity: inflation gap			0.930
Elasticity: output gap			1.732

Note: For welfare-optimal search, LPR policy function is "locked into" the welfare optimal form identified in Table 6.

Figure 1: IRFs to productivity shock

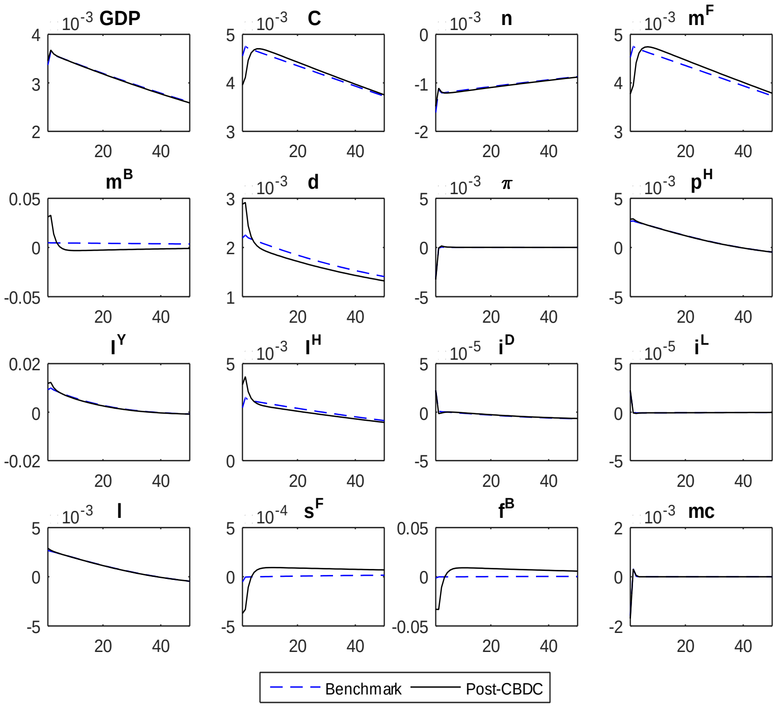


Figure 2: IRFs to housing productivity shock

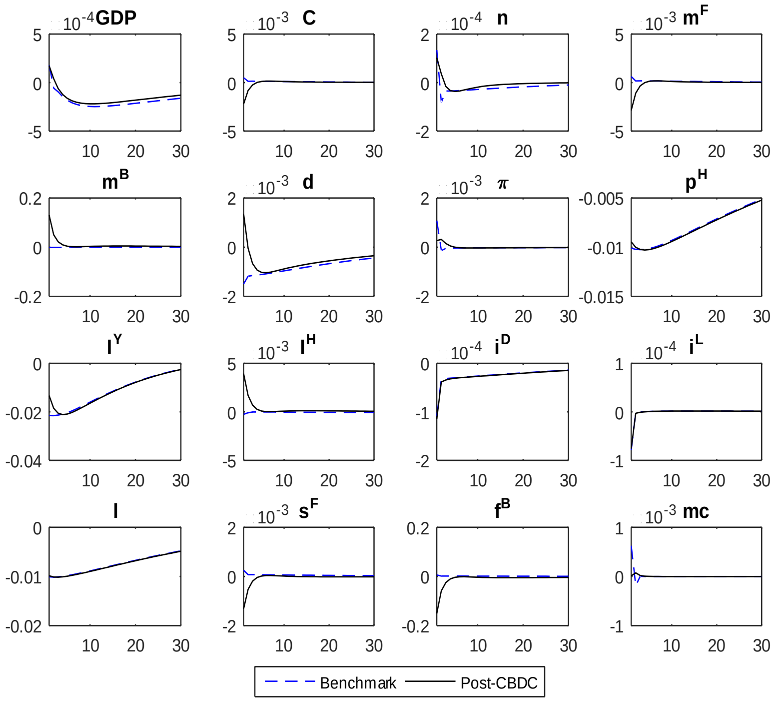


Figure 3: IRFs to paper money velocity-related shock

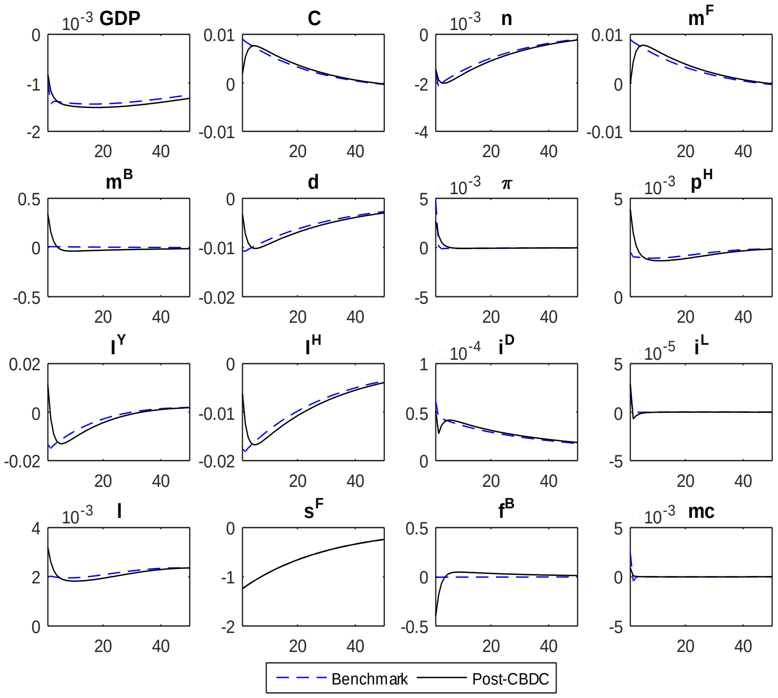


Figure 4: IRFs to LPR shock

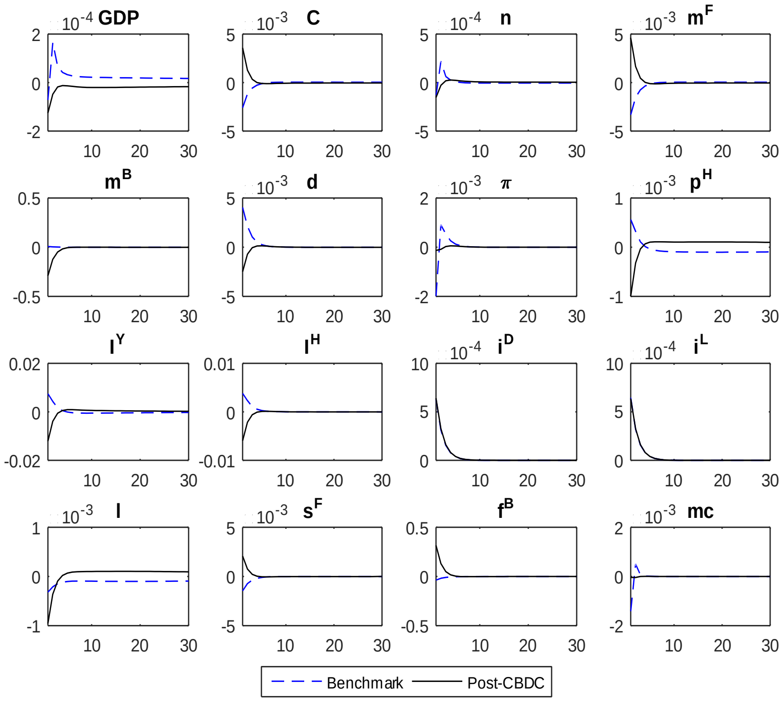
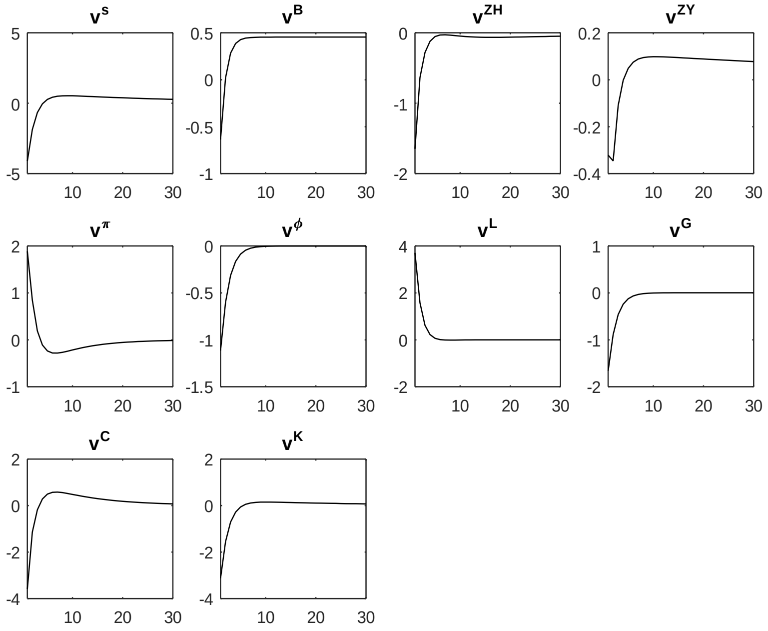


Figure 5: IRFs of m_t^{CD} to all shocks


v^S v^B v^{ZH} v^{ZY} v^π v^ϕ v^L v^G v^C v^K

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