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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 deposits and digital currencies to study the economic stability of two potential central banking policies in China, a Loan Prime Rate (LPR) policy function and central bank digital currency (CBDC) implementation. We Bayesian-estimate both a benchmark model and a "Post-CBDC world". In the post-CBDC world, although 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. We also uncover an optimal policy combination of the LPR rule and Taylor-style CBDC rule.

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 need for an expanded suite of central banking policies has 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, the 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 influences 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

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the preferential lending rates quoted by some of the largest commercial banks, which is then used as a reference lending rate in the economy. In essence, the new LPR provides the PBOC with more direct oversight and control of the market lending rate—albeit one that is based on targeted advisory and consultation of panel banks, almost all of which have the majority of active equity stakes by the State—similar to an official policy rate, but with the characteristics of a financial market stabilization tool.[2]

On the latter, the PBOC has recently initiated some selected Digital Yuan pilot programmes, with the CBDC being a centralized money fully backed by the PBOC.[3] In spite of a broad taxonomy on its potential characteristics, CBDC 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 monetary velocity-based transaction costs associated with the frequency of cash changing hands (Berentsen and Schär, 2018). Indeed, by using CBDC, the central bank will be in a position to pay negative interest rates on its liabilities to overcome the " zero lower bound" problem (Buiter, 2009; Agarwal and Kimball, 2015; Fischer, 2016), as well as preempting any crime and tax evasion issues associated with private digital currencies (PDC) (Rogoff, 2016).[4] As such, in a large economy such as China, where unaccounted monetary velocity could potentially exacerbate economic volatility, there is also a macro-financial stability angle to CBDC. In fact, apart from the various benefits associated with CBDC, the increasing attention garnered by PDC domestically (at one point China accounted for 90% of global trades in Bitcoins before the well-publicized " Cryptocurrency Ban" in 2017) has posed a greater risk to passive central banking (Bordo and Levin, 2017) and prompted the PBOC to be at the forefront of the initiative in introducing a CBDC, alongside the Swedish Riksbank (Agur et al., 2021).

In this article, we contribute to the literature by developing a dynamic stochastic general equilibrium (DSGE) model with cash deposits and digital currencies, both being used as payment options by households for consumption. The former is subject to velocity-related transaction costs similar to Barrdear and Kumhof (2016, 2022). 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 (2021) to account for the fact that housing assets are the most dominant financial assets held by Chinese households, accounting for almost 70% of the asset values of the majority of the households. To examine the cyclical implications and the qualitative differences between the current and the post-CBDC world (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 PDC (Hong et al., 2018; Schilling and Uhlig, 2019; Giudici et al., 2020), albeit with a significant holding/access cost due to the direct trading of PDC within China being restricted since 2018.[5] As such, unlike the cryptocurrency competition model of Fernández-Villaverde and Sanches (2019), there is only one type of PDC in our model (supplied by an

[2] One could argue that this is simply a quoted market consensus lending rate and not a policy tool per se. However, in a similar spirit to China's largest state-owned enterprises (SOEs) being effectively vehicles/tools of fiscal policy (Wen and Wu, 2019), China's largest state-owned banks often serve as vehicles/tools to influence liquidity and macro-stability of the domestic monetary system. Examples of empirical papers on the former are abundant (e.g, Liu et al., 2018; Zheng et al., 2018), where following the Great Recession majority of domestic credit expansion somehow only found their ways to the SOEs; whereas on the latter one needs not looking beyond the coordinated responses of Chinese banks in dramatically reducing NPLs and expanding regulatory capital ratios in the early 2000s (e.g., Li et al., 2020). Given that various PBOC releases in recent years have stressed the importance of managing the lending markets so as to keep the potential housing bubbles in check (Wang and Sun, 2013), we do believe LPR in itself can serve as a financial market stabilization tool.

[3] 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 the PBOC to have CBDC existing together with the current cash deposits, instead of a complete phase-out.

[4] Although our numerical policy experiments are mainly based on a context of negative CBDC rate, it is worth noting that it remains contentious in the current CBDC literature in terms of what constitutes an appropriate rate of returns for CBDC holding, and it is likely to differ across the context of different economies, including China. See, for example, Friedman's "full liquidity rule" (Friedman, 1969), and studies such as Chiu et al. (2019), Assenmacher et al. (2023), Mishra and Prasad (2023), which have suggested interest-bearing CBDC as potential policy tools that coexist with cash.

[5] This benchmark is necessary to support a meaningful investigation, instead of a case where we simply move from an economy without a 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). Indeed, as would have become clearer, it is precisely that, with this allowance of PDC to be used as payment instrument (more broadly, our PDC can also be interpreted as any form of offshore or illicit liquid assets), yet we find that PDC shock has very self-contained impact with regards to the overall business cycle of China in both pre- and post-CBDC world, means we are among the first contributions documenting the irrelevance of PDC in the macroeconomy of China whether it is banned or not.

exogenously fixed quantity), though its price is a source of stochastic shocks.[6]

The benchmark model is estimated for a pre-CBDC Chinese economy using Bayesian technique. 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 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 associated policy being a CBDC interest rate set by the Central Bank. The PDC is allowed to remain as an option too, with the set of policy instruments available to the Central Bank being: (i) the M2 growth rule; (ii) the LPR reaction rule for credit growth; and (iii) the CBDC interest rate. We then compare the two settings where: (i) in a benchmark post-CBDC case, the CBDC policy rate is set as a discount of the deposit rate; and (ii) the CBDC rate follows a Taylor-style reactionary rule type of setting. After evaluating the cyclicality properties between these different cases, we then consider various iterations of potential policy rules for both the CBDC interest and the LPR rate to identify optimal designs.

To preview, in the pre-CBDC world, we find an optimal LPR reaction function to be dependent on other assets than credit expansion (housing and physical capital market value growth). Conditional on this, in a subsequent optimal search for the post-CBDC world, we find the addition of an extra mandate to the growth of CBDC to be non-zero too. This suggests a potential interaction of these two seemingly unrelated central banking policies in the macro-financial stability agenda of the Chinese economy going forward. As such, 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.

Given these, our article is most closely related to the growing literature examining CBDC and its implementation, notably Barrdear and Kumhof (2016, 2022), though it is important to note that our model is significantly different from theirs to be more suitably aligned to key properties of the Chinese macroeconomy. Further, via our numerical experiments, we also contribute to the understanding of CBDC as " Reserves for All" (Niepelt, 2020), as well as other CBDC studies. For examples, 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. (2021), 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 adversely affect 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 Chinese macroeconomy), 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 a further understanding of the macroeconomic cyclicality of China in recent years, especially in the context of a model economy with three different central banking policies. More importantly, based on the estimated model, we then identify optimal policy designs for the LPR-setting and CBDC policy rate. In an environment where the 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 macro-financial stability, we believe our study, which at a minimum shows the existence of an optimal design for LPR- and CBDC rate-setting, would help to build further understanding of their macro-financial stabilization properties. 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.

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 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 deposit, 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 goods (CG) rented from a CG producer. The CG producer also rents out CG 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 LPR as a policy function, we assume the loan-to-value (LTV) 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

[6] Of course, as pointed out in studies such as Gans and Halaburda (2015), and Yermack (2015), we recognize that the debate about whether PDC can truly function as a medium of exchange remains largely contentious. Given that our main inclusion of it is mainly to facilitate the use of actual PDC price data to Bayesian-estimate that part of the model economy, we follow the standard convention and specify PDC as a possible payment tool, albeit with significant holding/access cost.

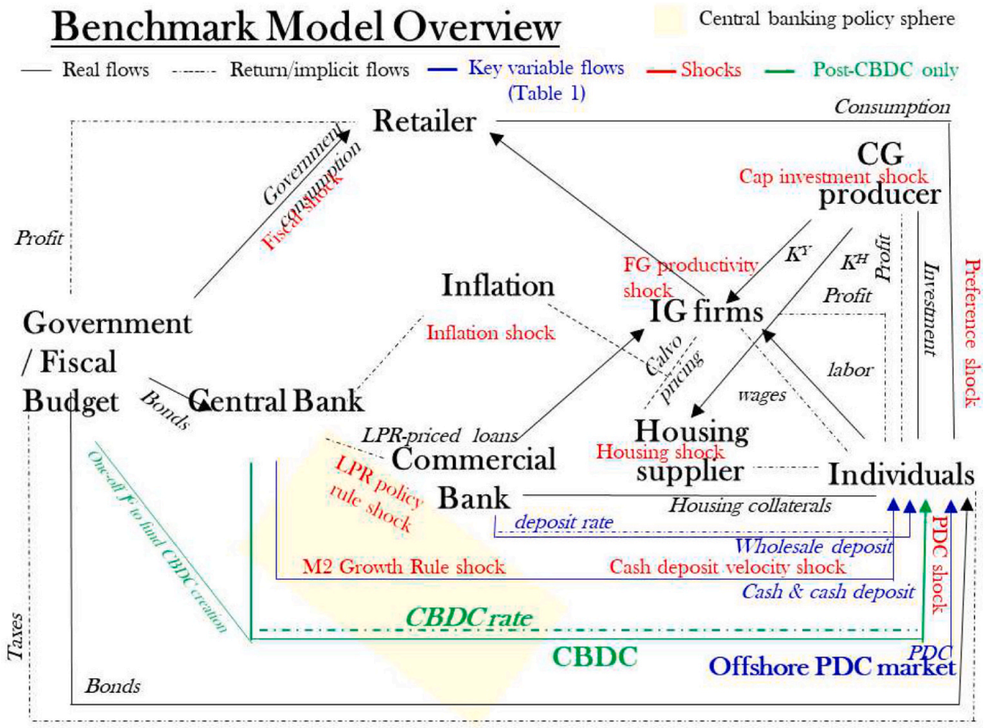

Fig. 1. Model overview.

LPR-setting, the Central Bank implements its monetary policy using an M2 (wholesale and cash 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. Fig. 1 illustrates the model overview. The presence of the government 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), and further illustration of the balance sheet implications between the pre- and post-CBDC world is presented in Fig. 2.

By design, the three types of money, as well as wholesale deposits, are not equivalent in our model, unlike the set-up in Brunnermeier and Niepelt (2019) and more significantly, Barrdear and Kumhof (2016, 2022). 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, the cash deposit is assumed to incur a monetary transaction cost tied to the velocity of circulation (Barrdear and Kumhof, 2016, 2022). However, unlike in their studies, for the centralized CBDC, we assume such a transaction cost to be zero to clearly distinguish the differences between the different types of monetary variables. While this is a strong assumption, it is also consistent with many studies that have argued for the improved transactionary efficiency (due to much cheaper and potentially costless settlements in a centralized DLT) of the PDC and CBDC (Ruttenberg and Pinna, 2016; Benos et al., 2019; Chiu and Koeppl, 2019; Priem, 2020; Cucculelli and Recanatini, 2022). In addition, although PDC transaction cost is zero, there are costs in access within China, and the cost is assumed to be an increasing function of the ratio of non-PDC to total money stock (to capture the network externality in 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 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 deposit (M_{ht}^{F}), digital currency [initially, only PDC, M_{ht}^{B}, in the benchmark pre-CBDC world; subsequently, CBDC, M_{ht}^{CD}, in addition to PDC in the post-CBDC world, is also made available as a choice variable], and observes the monetary transaction costs associated with cash deposit (s_t^F), as well as the cost of access incurred for holding PDC, f_t^B. The presence of these costs results in the individual choosing a $\xi_{ht} \in (0,1)$ fraction of final-goods consumption, C_{ht}, to be paid by cash deposit, and the remaining $1-\xi_{ht}$ by digital currencies. The individual also holds interest-yielding wholesale deposits, D_{ht} and government bonds,

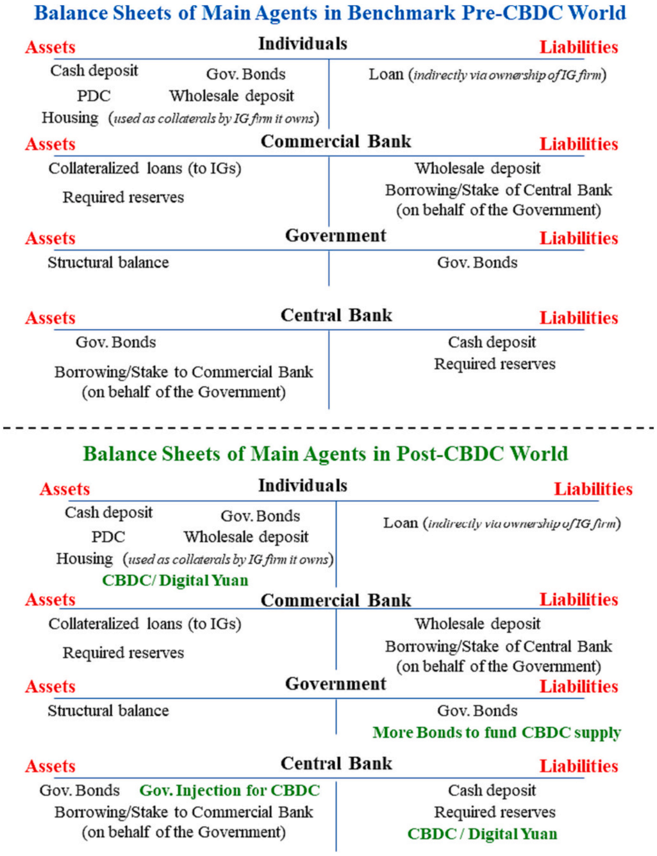

Fig. 2. Balance sheets of models.

Table 1
Salient characteristics of the different key monetary variables in the model.

	Cash deposit	PDC	CBDC	Wholesale deposit
	M_t^F	M_t^B	M_t^{CD}	D_t
Monetary transaction cost (velocity-based)	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
Ownership	Households	Households	Households	Households
Issuer/ Liability of:	Central Bank	Exogenous to the model	Central Bank	Commercial Bank

B_{ht}^{HD}.

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

$$U_t^h = \mathbb{E}_t \sum_{s=0}^{\infty} \beta^{t+s} \varepsilon_{t+s}^C \left[\begin{array}{c} lnC_{ht+s} + \eta_H lnH_{ht+s} \\ +\eta_M ln\left(\frac{M_{ht+s}}{P_{t+s}}\right) - \eta_N \frac{(N_{ht+s})^{1+\varsigma_N}}{1+\varsigma_N}, \end{array} \right] \tag{1}$$

where $\mathbb{E}_t$ is the expectation operator, $\beta \in (0,1)$ 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 $\varepsilon_t^C = (\varepsilon_0^C)^{1-\rho_C} (\varepsilon_{t-1}^C)^{\rho_C} exp(\nu_t^C)$, $\varepsilon_0^C > 0$, $\rho_C \in (0,1)$ the associated AR(1) coefficient, and ν_t^C the normally distributed error 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 deposit-payment share (ξ_{ht}), and the quantities of cash deposit (M_{ht}^F), PDC (M_{ht}^B), wholesale deposit (D_{ht}), and bonds (B_{ht}^{HD}), subject to the budget constraint,

$$\begin{aligned} &P_tC_{ht} + s_{ht}^F\xi_{ht}P_tC_{ht} + s_{ht}^D(1-\xi_{ht})P_tC_{ht} + P_t^H\Delta H_{ht} + B_{ht}^{HD} \\ &+M_{ht}^F + \left(1-f_{ht}^B\right)e_{t+1}\mathbb{E}_tP_{t+1}^BM_{ht}^B + D_{ht} \leq M_{ht-1}^F + e_tP_t^BM_{ht-1}^B + \left(1+i_{t-1}^D\right)D_{ht-1} \\ &+\left(1+i_{t-1}^B\right)B_{ht-1}^{HD} + P_t(w_tN_{ht}-T_{ht}) + \Pi_t^R + \Pi_t^K + \Pi_t^H, \end{aligned} \tag{2}$$

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 ($\mathbb{E}_te_{t+1}P_{t+1}^BM_{ht}^B$ 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.[7]

For the cash deposit-based transaction cost, s_{ht}^F, we use the specification of Barrdear and Kumhof (2016, 2022):

$$\begin{aligned} &s_{ht}^F = s\left(v_{ht}^F\right), \text{where } v_{ht}^F = \frac{\xi_{ht}P_tC_{ht}}{M_{ht}^F}, \\ &\text{with } s\left(v_{ht}^F\right) = s_{0,t} + A_Fv_{ht}^F + B_F\Big/v_{ht}^F - 2\sqrt{A_FB_F}, \end{aligned} \tag{3}$$

which satisfies the properties of increasing in v_{ht}^F, 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 deposit, $\underline{v}^F = \sqrt{\underline{B}/\underline{A}} > 0$. These ensure that $v_{ht}^F > \underline{v}^F$ holds at all times. In addition, $s_{0,t} > 0$ is assumed to follow an AR(1) process, $s_{0,t} = (\bar{s}_0)^{1-\rho_s}(s_{0,t-1})^{\rho_s}exp(v_t^s)$, with $\bar{s}_0 > 0$ being the non-zero steady-state transaction cost, $\rho_s \in (0,1)$ and v_t^s denote the persistence and random error terms respectively. Note that if $s_{0,t} = 0$, then the velocity of cash deposits, $v_{ht}^F = \sqrt{A_FB_F}/A_F\ \forall t$, 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 impulses of the non-centralized cash deposit circulations.

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

$$f_{ht}^B = f_h^B\left(\chi_{ht}^B\right), \text{where } \chi_{ht}^B = \frac{M_{ht}^B}{M_{ht}}, \ \text{ with } f_{ht}^B\left(\chi_{ht}^B\right) = f_0^B\left(\frac{1-\chi_{ht}^B}{1-\overline{\chi}^B}\right)^{\zeta_1}, \tag{4}$$

where $\zeta_1 \geq 0$. Although the economic rationale of f_{ht}^B is consistent with the 'regulatory hostile' landscape in China towards PDC, the specification of (4) is consistent with the literature. Specifically, it captures the network effects of Gans and Halaburda (2015), and Agur et al. (2021): the more PDC usage widens (as measured by its share in currency stock holdings, χ_{ht}^B), the less costly it is for said individual due to greater acceptance. Finally, for the CBDC introduced later, M_{ht}^{CD}, both the transaction and access costs are zero.

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

$$\frac{\mathbb{E}_tC_{ht+1}}{C_{ht}} = \mathbb{E}_t\left\{\frac{\beta\left(1+i_t^D\right)}{(1+\pi_{t+1})}\frac{\varepsilon_{t+1}^C}{\varepsilon_t^C}\left[\frac{1+s_{0,t}(2\xi_{ht}-1)+2\xi_{ht}\left(A_Fv_{ht}^F-\sqrt{A_FB_F}\right)}{1+s_{0,t+1}(2\xi_{ht+1}-1)+2\xi_{ht+1}\left(A_Fv_{ht+1}^F-\sqrt{A_FB_F}\right)}\right]\right\}, \tag{5}$$

$$\xi_{ht} = \sqrt{\frac{B_F\left(m_{ht}^F\right)^2}{C_{ht}\left(A_FC_{ht}+m_{ht}^F\right)}}, \tag{6}$$

$$\frac{w_t}{\eta_N(N_{ht})^{\varsigma_N}} = C_{ht}\left[1+s_{0,t}(2\xi_{ht}-1)+2\xi_{ht}\left(A_Fv_{ht}^F-\sqrt{A_FB_F}\right)\right], \tag{7}$$

$$\begin{aligned} &\eta_{H,t}C_{ht}\left[1+s_{0,t}(2\xi_{ht}-1)+2\xi_{ht}\left(A_Fv_{ht}^F-\sqrt{A_FB_F}\right)\right] \\ &= \left(p_t^HH_{ht}\right) - \mathbb{E}_t\left[\beta\frac{\varepsilon_{t+1}^C}{\varepsilon_t^C}(1-\delta_H-\varphi\varkappa)\frac{(1+\pi_{t+1})}{\left(1+i_t^D\right)}p_{t+1}^HH_{ht}\right], \end{aligned} \tag{8}$$

[7] As seen later in the *Housing Supply* section, the change in the 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.

$$m_{ht}^{F} = \mathbb{E}_t \left\{ \begin{array}{c} \left(1 - e_t P_{t+1}^{B} + \dfrac{e_{t+1} P_{t+1}^{B}}{1+i_t^D}\right) \dfrac{1}{A_F} \\ + \dfrac{f_{ht}^{B}}{A_F} \left[e_{t+1} P_{t+1}^{B} \left(1 - \zeta_1 \chi_{ht}^{B}\right) - \dfrac{\zeta_1 \left(\chi_{ht}^{B}\right)^2}{\left(1 - \chi_{ht}^{B}\right)} \right] + \dfrac{B_F}{A_F} \end{array} \right\}^{-0.5} \xi_{ht} C_{ht}, \tag{9}$$

$$m_{ht}^{B} = \mathbb{E}_t \left\{ \begin{array}{c} 1 - \dfrac{1}{\zeta_1 \chi_{ht}^{B}} \\ + \dfrac{1}{\zeta_1 f_{ht}^{B}} \left[1 + \dfrac{(e_{t+1}/e_t)}{\left(1+i_t^D\right)} \right] \end{array} \right\}^{-1} \left[\frac{\eta_M w_t \left(1+i_t^D\right)}{\zeta_1 \eta_N (N_{ht})^{\varsigma_N} f_{ht}^{B}} \frac{(e_{t+1}/e_t)}{e_{t+1} P_{t+1}^{B}} \right], \tag{10}$$

where $m_{ht}^F = M_{ht}^F/P_t$, $m_{ht}^B = M_{ht}^B/P_t$ are the real values of the currencies, $\mathbb{E}_t\left(1+\pi_{t+1}^H\right) = P_{t+1}^H/P_t^H$ 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. (5) is the Euler equation, which in this model is influenced by the payment transaction cost of cash deposit; (6) shows the optimal fraction of payment made using cash deposits, ξ_{ht}; (7) is individual h's labor supply equation that equates marginal utility of leisure to that of consumption; (8) presents the intra-temporal substitution condition between the marginal demand for housing and marginal consumption; (9) is individual h's real demand function for cash deposits; (10) 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 wholesale deposits and wages.

In terms of PDC supply, unlike Schilling and Uhlig (2019), we abbreviate from detailed modeling of the mining protocols 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 the steady state). 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 the 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 calls for the PDC spot prices, P_t^B, to evolve according to:

$$P_{t+1}^B = P_t^B + \varepsilon_t^B, \text{where} \quad \varepsilon_t^B = (1-\rho_B)\overline{\varepsilon}^B + \rho_B \varepsilon_{t-1}^B + v_t^B, \quad v_t^{B} \sim N\left(0, \sigma_B^2\right), \tag{11}$$

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 (11) also implies $\Delta P_{t+1}^B = \varepsilon_t^B$, if $\rho_B = 0$, then the change in the spot price of PDC would follow a random walk process with a positive drift of $\overline{\varepsilon}^B$ over time. Nevertheless, given that (11) can also be written as $P_{t+1}^B/P_t^B = 1 + \left(\varepsilon_t^B/P_t^B\right)$, in a steady-state equilibrium, $\overline{\varepsilon}^B = 0$ must hold, which implies a fundamental/intrinsic value of zero—–consistent with the assertion of studies such as Cheah et al. (2018). In our view, given the relative ease of access to the prices 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 and Stiglitz (1977) technology,

$$Y_t = \left\{ \int_0^1 [Y_{it}]^{(\theta-1)/\theta} di \right\}^{\theta/(\theta-1)}, \tag{12}$$

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

$$Y_{it} = \left(\frac{P_{it}}{P_t}\right)^{-\theta} Y_t, \tag{13}$$

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,

$$Y_{it} = Z_t^Y \left(K_{it}^Y\right)^{\alpha} (A_t N_{it})^{1-\alpha}, \tag{14}$$

where $\alpha \in (0,1)$, N_{it} is the labor input, K_{it}^Y is CG rented by firm i at a cost, P_t^{KY}, from the CG 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 Gita, 2007; Garca-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, $Z_t^Y = (\overline{Z}^Y)^{1-\rho_{ZY}}(Z_{t-1}^Y)^{\rho_{ZY}} exp(v_t^{ZY})$, 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, $\forall i$,

$$mc_t = \frac{\Phi_Y}{Z_t^Y}\left(\frac{P_t^{KY}}{P_t}\right)^{\alpha}\left[\frac{(1+i_t^L)w_t}{A_t}\right]^{1-\alpha}, \text{where } \Phi_Y = \alpha^{-\alpha}(1-\alpha)^{\alpha-1}, \text{which also implies} \tag{15}$$

$$\frac{(1+i_t^L)w_t}{(P_t^{KY}/P_t)} = \left(\frac{1-\alpha}{\alpha}\right)\frac{K_{it}^Y}{N_{it}}. \tag{16}$$

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 and Wouters (2003) type of indexation rule, $P_{it+s} = P_{it}\left(\frac{P_{t+s-1}}{P_{t-1}}\right)^{\rho}$, $\rho \in (0,1)$, and a probability $1-\omega$ in re-optimizing its price. The optimal reset price, P_{it}^*, solves:

$$\mathbb{E}_t \sum_{s=0}^{\infty} (\varpi\beta)^s \left\{ V_{t,s}\left[\frac{P_{it}^*}{P_{it+s}} - \frac{\theta}{(\theta-1)}mc_t\right]Y_{it+s}\right\} = 0, \tag{17}$$

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 (17), and then log-linearizing it and the IG price equation, we derive a Gal and Gertler (1999) style hybrid New Keynesian Phillips curve (NKPC):

$$\widehat{\pi}_t = \frac{\beta}{1+\beta\varrho}\mathbb{E}_t\widehat{\pi}_{t+1} + \frac{\varrho}{1+\beta\varrho}\widehat{\pi}_{t-1} + \frac{(1-\varpi)(1-\varpi\beta)}{\varpi(1+\beta\varrho)}\widehat{mc}_t + \widehat{\varepsilon}_t^{\pi}, \tag{18}$$

which relates the log-deviation of inflation (from the steady state), $\widehat{\pi}_t$, to both the past and future inflation, as well as the log-deviation in real marginal cost, $\widehat{mc}_t$. $\widehat{\varepsilon}_t^{\pi}$ 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 CG, 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,

$$IH_t = Z_t^H (K_t^H)^{\iota}, \tag{19}$$

where $\iota \in (0,1)$, and Z_t^H follows an AR(1) process, $Z_t^H = (\overline{Z}^H)^{1-\rho_{ZH}}(Z_{t-1}^H)^{\rho_{ZH}} exp(v_t^{ZH})$, 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:

$$\frac{P_t^H}{P_t^{KH}}IH_t = \frac{K_t^H}{\iota}. \tag{20}$$

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 the housing depreciation rate. Given this, 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:

$$P_t^H \Delta H_t = P_t^H[H_t - (1-\delta_H - \varphi\chi_{t-1})H_{t-1}]. \tag{21}$$

2.4. Capital good producer

There is a CG producer, collectively owned by the private individuals, who buys gross amounts, I_t^Y and I_t^H, of final goods from the retailer in each period to produce CGs, 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 CG for the two types, K_{t+1}^j, $j = Y, H$, therefore accumulate as:

$$K_{t+1}^j = Z_t^K\left[I_t^j - \frac{\Theta_j}{2}\left(\frac{K_{t+1}^j}{K_t^j} - 1\right)^2 K_t^j\right] + (1-\delta^{Kj})K_t^j, \tag{22}$$

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, 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 CG producer chooses the level of 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[8]:

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

subject to (22), which yields for K_{t+1}^j, $j = Y,H$:

$$\mathbb{E}_t\frac{P_{t+1}^{Kj}}{P_{t+1}} = \left[\frac{1}{Z_t^K} + \Theta_j\left(\frac{K_{t+1}^j}{K_t^j} - 1\right)\right]\left(\frac{1+i_t^D}{1+\pi_{t+1}}\right) - \frac{(1-\delta^{Kj})}{Z_{t+1}^K} - \frac{\Theta_j}{2}\left[\left(\frac{K_{t+2}^j}{K_{t+1}^j}\right)^2 - 1\right]. \tag{23}$$

2.5. Commercial Bank

There is a representative commercial bank collectively owned by the individuals. As in studies such as Ravenna and Walsh (2006), and 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 firm to use the housing units of its owner collaterals, hence giving a collateral constraint of

$$(1+i_t^L)L_{it} = \varkappa \mathbb{E}_t P_{t+1}^H H_{it}, \tag{24}$$

where $(1+i_t^L)$ is the gross lending rate, which, for convenience, is assumed to be directly set at the LPR rate dictated by the Central Bank, given the context of China. $\varkappa \in (0,1)$ is the 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 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 wholesale deposits, D_t, and the net stake of 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 $(1-\varphi_t)(1+i_t^L)L_t + \varphi \varkappa_t \mathbb{E}_t P_{t+1}^H H_t = (1+i_t^D)(D_t + J_t^{CB})$, or equivalently, using (24),

$$\frac{(1+i_t^L)}{(1+i_t^D)} = \frac{(D_t + J_t^{CB})}{L_t}, \tag{25}$$

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. Further, in our benchmark case, due to the collateral constraint (24) being always binding, the default term drops out in (25) and therefore has no role to play in the business cycle. As robustness, in the later section we consider two extension/sensitivity specifications: i) costly recovery of collaterals, therefore making default probability, φ becoming material in (25); and ii) an " LTV-as-policy tool" scenario similar to Rubio and Carrasco-Gallego (2014), Rubio and Yao (2020), in which then LPR, i_t^L, is determined endogenously instead. Indeed, irrespective of whether LPR is set by the Central Bank (as in the benchmark case) or as an endogenous variable determined by standard "demand-supply" dynamics, we preview that our findings later are qualitatively consistent across these different specifications.

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

$$L_t + R_t = D_t + J_t^{CB}, \text{or equivalently}, L_t = (1-\mu)D_t + J_t^{CB}, \tag{26}$$

where J_t^{CB} is a net flow term that captures the stake of the Central Bank (held on behalf of the government).

2.6. Government and central banking

To concentrate on Central Banking policies but allow for policy spaces/rooms to finance CBDC supply, 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

[8] 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}, as those of the household problem.

variance (σ_G^2). The period-specific fiscal budgetary constraint is therefore:

$$B_t^D - \left(1 + i_{t-1}^B\right)B_{t-1}^D = P_t(G_t - T_t) + J_t^G, \tag{27}$$

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 in Fig. 2 earlier, 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:

$$B_t^{CD} + J_t^{CB} + J_t^G = M_t^F + R_t. \tag{28}$$

For convenience, we assume the Central Bank keeps its real holding of domestic government bonds constant, 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 have 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 $\phi_t = \left(m_t^F + d_t\right)/\left(m_{t-1}^F + d_{t-1}\right)$, we have:

$$\phi_t = \overline{\phi}\left(\frac{1+\pi_t}{1+\pi^T}\right)^{\nu_1^m}\left(\frac{GDP_t}{\overline{GDP}}\right)^{\nu_2^m}\varepsilon_t^{\phi}, \tag{29}$$

where $\nu_1^m, \nu_2^m \in \mathbb{R}$, π^T is the inflation target, $\overline{GDP} = \overline{Y} + \frac{\overline{P}^H}{\overline{P}}\overline{I}^H$ 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, $\varepsilon_t^{\phi} = \left(\varepsilon_0^{\phi}\right)^{1-\rho_\phi}\left(\varepsilon_{t-1}^{\phi}\right)^{\rho_\phi} exp\left(\nu_t^{\phi}\right)$, where $\varepsilon_0^{\phi} = 1$, $\rho_\phi \in (0,1)$, and ν_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:

$$1 + i_t^L = \left(1 + \overline{i}^L\right)\left(\frac{l_t}{l_{t-1}}\right)^{\nu_1}\varepsilon_t^L, \tag{30}$$

where $\nu_1 \geq 0$, and $\overline{i}^L$ 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 $\varepsilon_t^L = \left(\varepsilon_0^L,\right)^{1-\rho_L}\left(\varepsilon_{t-1}^L\right)^{\rho_L} exp\left(\nu_t^L\right)$, where $\rho_L \in (0,1)$ is the AR(1) coefficient, and ν_t^L is the zero-mean error term with a constant variance (σ_L^2).

In the post-CBDC world, the Central Bank would be armed with an additional policy tool, on top of the benchmark pre-CBDC M2 growth rule and the LPR reaction function. As discussed in Section 1, there is 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 contentious debate in the current CBDC literature in terms of what constitutes an appropriate rate of returns for CBDC. In addressing (ii), we follow studies such as Agarwal and Kimball (2015), and Rogoff (2016) to consider the possibility of having CBDC trading below par compared to other Central Bank liabilities. As such, in the post-CBDC world, we model 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, $1 + \overline{i}^{CD} < 1$.

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

In terms of the dynamic system, on top of (5)–(10), an additional first-order condition is derived, which in a symmetric equilibrium gives the real demand for CBDC:

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

[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.

Table 2
Summary of data sources and treatments.

Time series	Measurement	Source	Normalised by *CPI*?	Normalised by *pop*?	Natural log?	SA	Data Frequency Conversion
GDP_t	Gross domestic product	NBSC	√	√	√	√	Converted to monthly by QM
C_t	Private consumption	NBSC	√	√	√	√	Converted to monthly by QM
I_t	Private investment	NBSC	√	√	√	√	Converted to monthly by QM
P_t^B	Nominal bitcoin price	CMC	N.A.	N.A.	√	√	Actual monthly series available
IH_t	New housing flows	NBSC	N.A.	√	√	√	Converted to monthly by QM
p_t^H	House Price Index (HPI)	CREIS	√	N.A.	√	√	Actual monthly series available
π_t	CPI inflation	FRED	N.A.	N.A.	N.A.	√	Actual monthly series available
N_t	Total labour hours	MLSS &NBSC	N.A.	√	√	√	Interpolated to monthly by implied monhly CAGR
i_t^L	Nominal market loan/ lending rate/LPR	Bloomberg & estimation	N.A.	N.A.	N.A.	√	Estimated, by monthly REPO with avg. interest spread of 4 largest banks
pop_t	Working-age population index	NBSC	N.A.	N.A.	N.A.	√	Interpolated to monthly by implied monthly CAGR

NBSC - National Bureau of Statistics of China;
CMC - CoinMarketCap.
FRED - Federal Reserve Bank of St. Louis.
MLR - Ministry of Land and Resources, P.R.C.
MLSS - Ministry of Labour and Social Security, P.R.C.
PBoC - People's Bank of China;
CREIS - China Real Estate Index System.
QM: quadratic method.
CAGR: Compoumd annualised growth rate.

Table 3
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	Cash deposit transaction cost, 1	0.0098
B_F	Cash deposit 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

where there is a direct trade-off to the cash deposit, and inversely dependent on the interest spread between wholesale deposit and CBDC.

Further, while we have attempted to keep all the policy functions at their benchmark version throughout our analyses, in the subsequent optimality search exercises later in the paper, we also consider a different form of LPR reaction function [from that of (30)] due to $\nu_1 = 0$ being found as the optimal ν_1 (i.e., a reaction to credit expansion mandate is not necessary). In that specific instance, we then consider, for the " no CBDC" world an LPR policy function of:

$$1+i_t^L = \left(1+\bar{i}^L\right)\left(\frac{P_{t+1}^H H_t}{P_t^H H_{t-1}}\right)^{o_H}\left(\frac{P_{t+1}^K K_t}{P_t^K K_{t-1}}\right)^{o_K}\varepsilon_t^L, \tag{32}$$

where $P_{t+1}^K K_t = P_{t+1}^{KH} K_t^H + P_{t+1}^{KY} K_t^Y \; \forall t$, and for the post-CBDC world,

Table 4
Summary statistics for prior and posterior distribution of parameters.

Parameter	Prior distribution			Posterior	
	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

$$1+i_t^L = \left(1+\bar{i}^L\right)\left(\frac{P_{t+1}^H H_t}{P_t^H H_{t-1}}\right)^{o_H}\left(\frac{P_{t+1}^K K_t}{P_t^K K_{t-1}}\right)^{o_K}\left(\frac{m_t^{CD}}{m_{t-1}^{CD}}\right)^{o_{CD}}\varepsilon_t^L, \tag{33}$$

which allows for the possibility of LPR-setting to be dependent on growth in other asset markets within our model, including the CBDC after its rollout.

Likewise, we also consider two settings in the post-CBDC world for CBDC interest rate-setting: i) in the baseline, we simply set CBDC return to be a constant discount of the wholesale deposit rate, $1+i_t^{CD} = \left(1+i_t^D\right) - 0.08$; and ii) when searching for an optimal policy design, we consider a " price-targeting benchmark rule" suggested by Bordo and Levin (2017), as in:

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

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

Finally, assuming that the Central Bank always stands ready to meet all CBDC demand, the CBDC market will be in equilibrium, with its period-specific balance sheet equals:

$$B_t^{CD} + J_t^{CB} + J_t^G = M_t^F + M_t^{CD} + R_t. \tag{35}$$

3. Equilibrium and evaluations: 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 ($v_{ht}^F = v_t^F$), the same cash deposit payment 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:

Table 5
Variance decomposition analysis - benchmark model (No CBDC).

Variables	Structural Shocks									
	Cash deposit 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 deposits, 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
Wholesale 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
W.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
Cash dep. 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

$$GDP_t = C_t + \frac{\overline{P}^H}{\overline{P}} I_t^H + I_t^K + G_t, \tag{36}$$

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 does not dramatically affect GDP growth.

In real terms, the government bonds market-clearing conditions are 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 and wholesale deposits, 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 $\left\{C_t, N_t, Y_t, b_t^{HD}, b_t^{CD}, b_t^D, d_t, m_t^B, m_t^F, l_t, H_t, K_t^H, K_t^Y\right\}$ and costs $\left\{s_t^F, f_t^B, mc_t\right\}$, 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.

To implement our computational policy analyses, we first Bayesian estimate and solve the benchmark model of the pre-CBDC world. After that, based on the estimated deep parameter values of the benchmark model for China, we solve again the more expanded post-CBDC world dynamic system. We then compare and contrast the variance decomposition and the IRFs in both worlds, as well as evaluate how optimal central banking policy designs would change moving from the pre- to the post-CBDC world.

In summary, on the former (collectively known as cyclicality analyses), in the pre-CBDC world, the policy tools available for the Central Bank include: (i) the M2 growth rule (29); and (ii) the benchmark LPR reaction rule (30). In the post-CBDC world, the policy tools become: (i) the M2 growth rule (29); (ii) the benchmark LPR reaction rule (30); and (iii) the simple discounted CBDC rate regime (from the wholesale deposit rate).

On the latter, which concerns optimal grid search, in the pre-CBDC world, we first implement grid search for optimal policy parameters based on: (i) the M2 growth rule (29); and (ii) the benchmark LPR reaction rule (30). It turns out that the policy mandate with

Table 6
Variance decomposition analysis - post-CBDC world.

Structural Shocks										
Variables	Cash deposit 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 deposits, 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
Wholesale 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
W.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
Cash dep. 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

regards to credit expansion in the latter is redundant. We then consider the LPR reaction rule of (32). In the post-CBDC world, our grid search for optimal policy parameters then become a set of grid search exercises based on: (i) the M2 growth rule (29); (ii) a modified LPR reaction rule to (32), as in the version of (33) where CBDC growth is added; and (iii) the simple discounted CBDC rate regime. Finally, when we are able to lock in the optimal policy parameter values for the LPR reaction rule in (33), then we consider the Taylor rule-style CBDC interest rate function of (34). In short, unless a policy is specifically mentioned, throughout our optimal search exercises later (irrespective of for pre- or post-CBDC world), we keep the policy functions *not involved* in optimal search to be at the estimated benchmark forms, so as to be in line with the initial benchmark economy.

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 follows. 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 ($T = 74$). Table 2 shows the summary of data sources and treatment. 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 top commercial banks. Specifically, starting from the monthly series of market-based REPO rates 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. In terms of data sources, GDP, consumption,

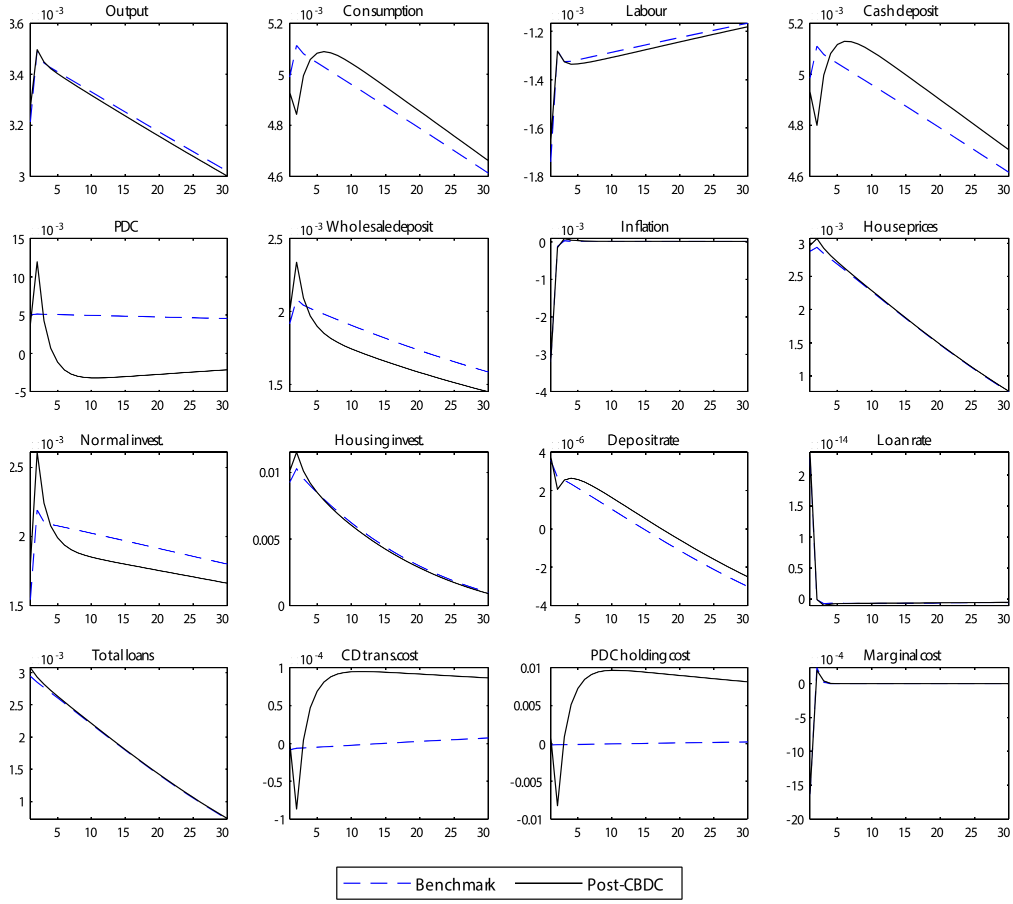

Fig. 3. IRFs to productivity shock.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

private investment, labour and population are collected from the National Bureau of Statistics of China (NBSC). Bitcoin price, house price index and LPR originated from CoinMarketCap (CMP), China Real Estate Index System (CREIS) and Bloomberg respectively.

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]. Following Liu and Ou (2021), the remaining parameters are calibrated to match the initial steady-state values of key macroeconomic ratios to the long-run state of China from 1952–2014: consumption-to-GDP ratio of 52%, non-residential investment ratio of 32%, residential investment ratio of 3%, government spending ratio of 15%. We also calibrate the cash-to-GDP ratio of 13% and the bitcoin market capitalization-to-GDP ratio of 0.3%, which are approximately consistent with the average of the actual data from 2000 to 2019, the longest data available. 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 3. 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, 2021), 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 a 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 cash deposits 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 capitalization-to-GDP ratio.

Next, the elasticity of IG with respect to the capital stock, α, is set at 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 the capital stock, $\iota = 0.2$, is set following Liu and Ou (2021). The loan default probability, $\varphi = 0.0292$ is set in accordance with those reported by the China Banking and Insurance Regulatory Commission. The reserve requirement

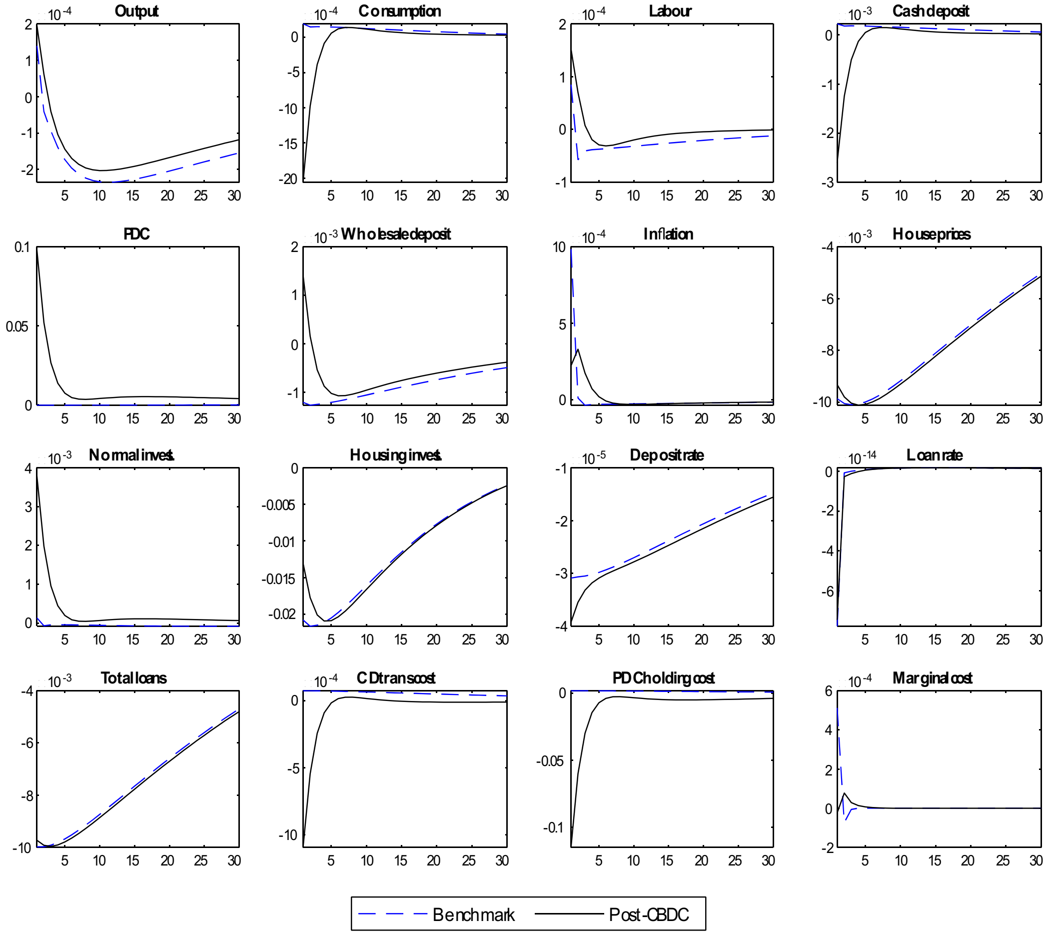

Fig. 4. IRFs to housing productivity shock.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

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 4 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 the housing market (Minetti et al., 2019; Liu and Ou, 2021) 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 the meta-analysis of Chetty et al. (2011). The prior for the money-holding utility weight, η_M, is set at 0.025, following Agénor et al. (2014). The priors of the two parameters in the NKPC ($\varpi = 0.67, \rho = 0.5$) follow Liu and Ou (2021), 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 'speak'. Next, we deal with the M2 growth rule and LPR policy function, both of which are 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 'speak' 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,

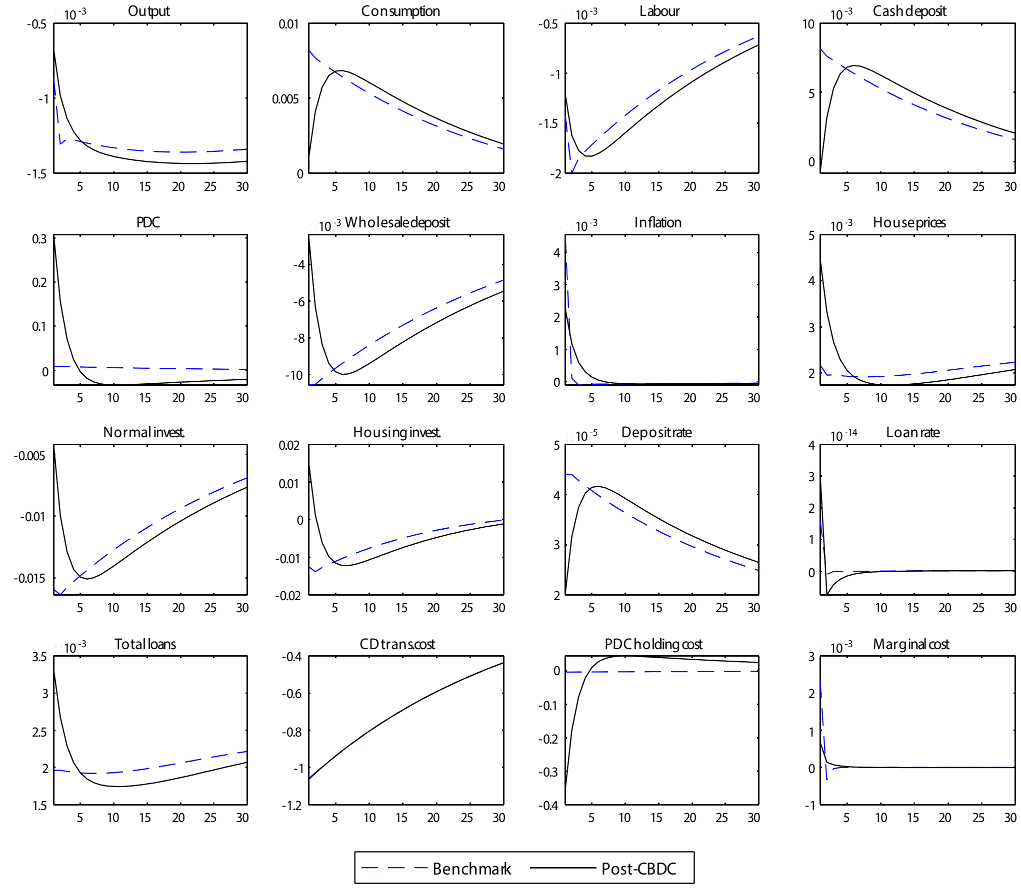

Fig. 5. IRFs to cash deposit velocity-related shock.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

such as Christiano et al. (2005), Smets and Wouters (2003), and 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 (2021). 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 the range of the estimates usually obtained in the aforementioned Bayesian DSGE literature, including Iacoviello and Neri (2010). Alternatively, the estimated value may imply a high adjustment 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 LPR and total loan growth in the Chinese economy.

5. Analysis

First, we examine the estimated results for both variance decomposition and IRFs of the benchmark model without CBDC. Next, to examine " how things would change" post-CBDC implementation, we then analyze the variance decomposition and IRFs in the post-CBDC world. Specifically, this first 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. Note that when evaluating the IRFs, we focus more on the qualitative aspects than the precise quantitative differences. Specifically, we are concerned about whether the direction of the instantaneous responses immediately after the shocks is the same or not, and whether post-CBDC implementation increases/decreases persistence. Note also that throughout the cyclicality analyses, all parameters are set at their benchmark values,

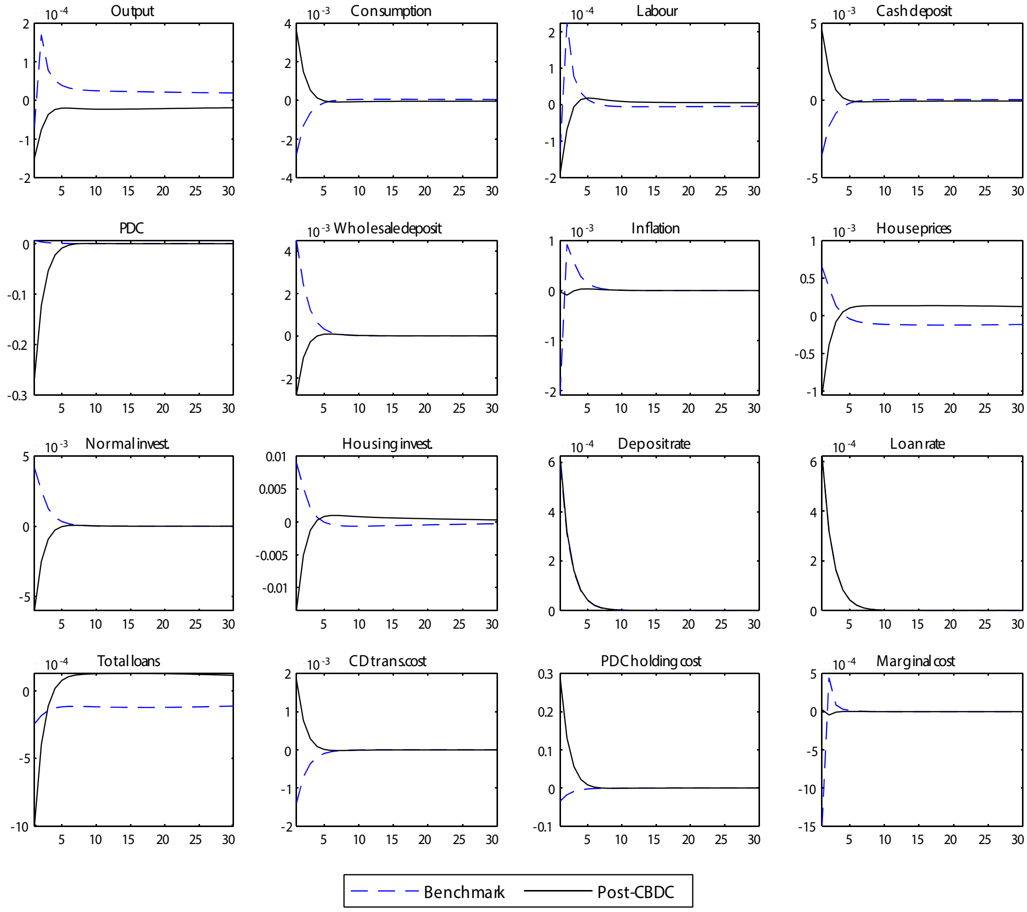

Fig. 6. IRFs to LPR shock.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

and the relevant policy parameters of the Central Bank are therefore based on the Bayesian-estimated values. We have not considered any optimality analysis yet.

By implications, when conducting cyclicality analyses, the policy framework in place for the pre-CBDC world includes: (i) M2 growth rule (29); and (ii) the benchmark LPR reaction rule (30). Both are based on Bayesian-estimated parameters to reflect the contemporary state of the Chinese economy. In the post-CBDC world, on top of those two, the simple discounted CBDC rate regime (from the wholesale deposit rate) is also introduced. Based on these setups, we then consider the robustness of our cyclicality analyses using two model extensions discussed earlier.

The second part then involves the search for an optimal design of the new monetary policy regime. It is here that we allow the policy rules to deviate from their benchmark forms in search of a welfare-optimal policy cocktail. Specifically, we search for the optimal design of policy rules for the three central banking policies, based on an objective function of maximizing the aggregate version of (1), as in a welfare function of:

$$maxW_t = \mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \begin{bmatrix} lnC_{t+s} + \eta_H lnH_{t+s} \\ +\eta_M ln(m_{t+s}) - \eta_N \frac{(N_{t+s})^{1+\varsigma_N}}{1+\varsigma_N}. \end{bmatrix} \tag{37}$$

5.1. Variance decomposition and impulse responses

Table 5 and Table 6 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% of the variations in GDP, consumption, labor supply, and cash deposit (see Liu and Ou, 2021; Minetti and Peng, 2018), therefore reaffirming the reasonability of our estimated model in modeling China. This is despite the monthly frequency applied in our Bayesian estimation. After that, preference shock and the cash deposit velocity-related shock are the

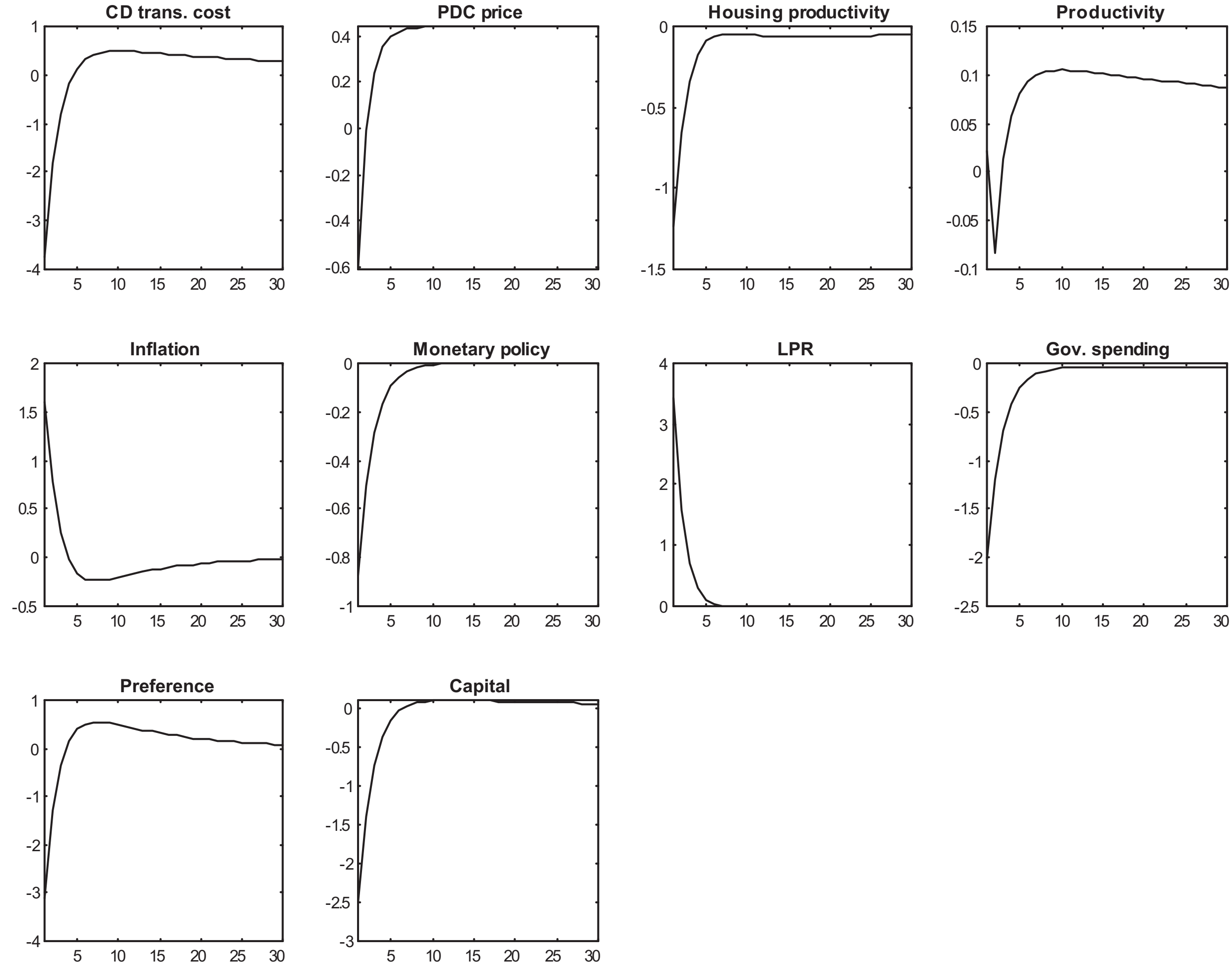

Fig. 7. IRFs of m_t^{CD} to all shocks, post-CBDC scenario.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

most significant drivers of economic volatility. The former is consistent with the characteristics of most DSGE models, and preference shock is observed to be one of the top three drivers of variations for all but five of the variables presented in Table 5. By design, conventional money velocity is 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 are captured by the demand-side shock, instead of the structural shock within the M2 supply growth rule. Intuitively, we believe that this reflects the relative unknown of the drivers of payment velocity in China, where a geographically dispersed economy with significant rural sectors means any residual volatility is likely to be captured by this structural shock, instead of the M2 supply growth 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), and Liu and Ou (2021), it appears that variations in loans in the Chinese economy are predominantly driven by the housing market, as 56.86% 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 macro-financial stability in China, it may distort the appetite for domestic government bonds, just like any offshore (legal or illicit) liquid assets would do.

We then consider the results in Table 6, which concerns the post-CBDC world. Post-implementation of CBDC, we see that the dominant role of productivity shock remains, followed by preference shock and cash deposit 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

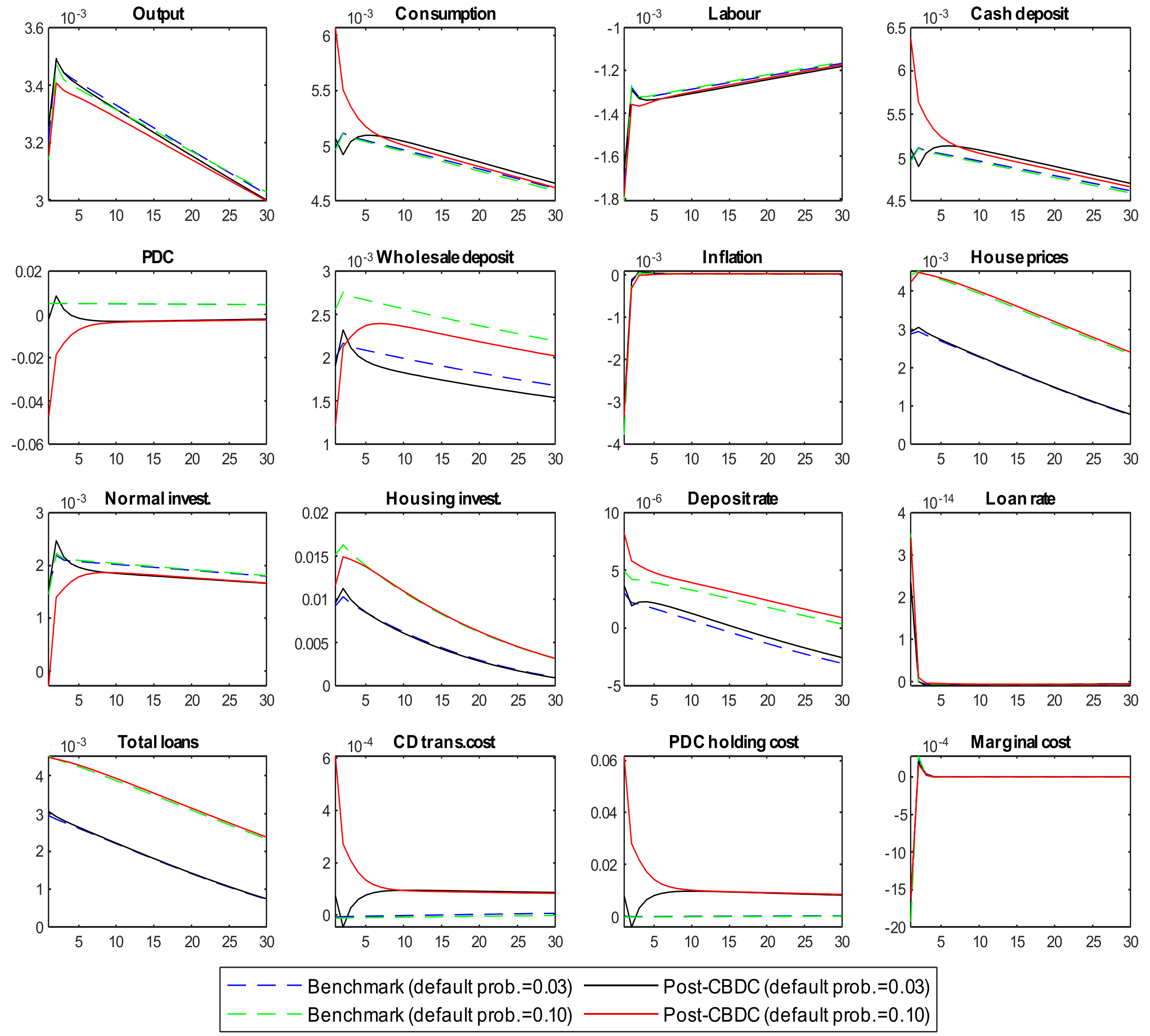

Fig. 8. IRFs to productivity shock with different default probabilities.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

associated with LPR. While this could merely reflect computational anomalies, these do suggest that the introduction of CBDC could have a portfolio reallocation effect that exhibits improved stabilization of the economy, 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 deposit velocity-related shock, preference shock, and LPR-related shock. In contrast, for the CBDC interest rate, the primary drivers are cash deposit 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 payment, would have a significant effect on the private holdings of CBDC. Indeed, in a regime where cash deposits will coexist with CBDC (as in China), then the designated return for CBDC is potentially dependent on the velocity of existing cash deposits' circulation.

Figs. 3–6 compare the IRFs of key variables to four shocks between the pre- and the post-CBDC world. Given its dominant role, Fig. 3 illustrates the IRFs to one standard-deviation productivity shock. Qualitatively, the IRFs are largely within expectation, where GDP, consumption and investments are pro-cyclical. These are the same for the demand for cash deposits, loans, PDC, wholesale deposits, and 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 deposit (m_t^F), wholesale deposit (d_t),

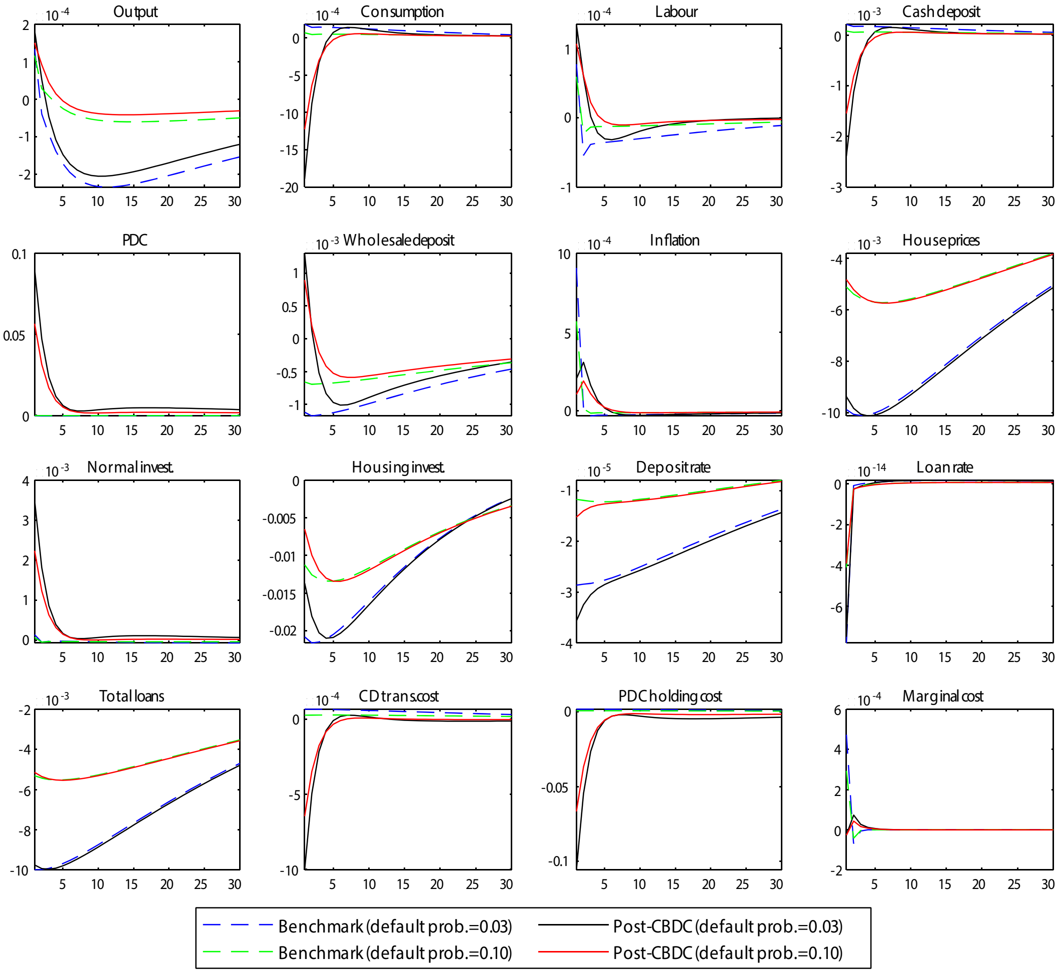

Fig. 9. IRFs to housing productivity shock with different default probabilities.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

and PDC (m_t^B), the presence of CBDC amplifies the effects of productivity shock, though there is no noticeable difference in the persistence of adjustment path (except for m_t^B). Next, Fig. 4 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 being much more volatile. In essence, the presence of CBDC would provide a source of amplification, leading to a 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 deposit velocity-related transaction cost (presented in Fig. 5) do not show a noticeable difference between the pre- 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 the adjustment path. Indeed, when we examine the IRFs of variables in response to a one standard-deviation shock to LPR in Fig. 6, the opposite is observed. Specifically, in the case of a stochastic shock to LPR, the post-shock transition path of variables appears to be less volatile in the post-CBDC world. Indeed, the transition path of selected variables also appears to be less persistent, notably for loans, inflation, and housing prices. 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 mitigating this due to its improved stabilization properties in the post-CBDC world. Indeed, in Fig. 7, 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.

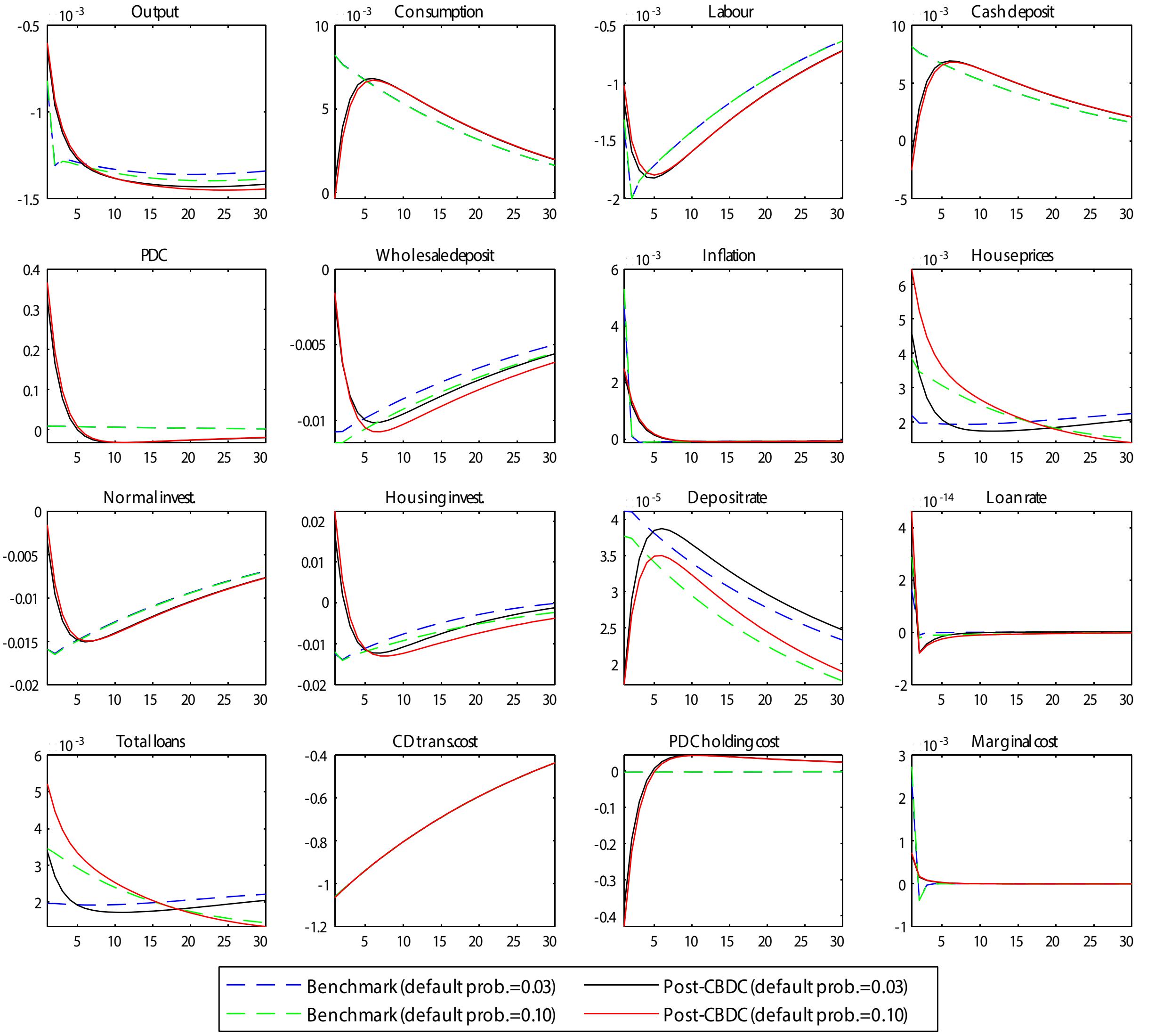

Fig. 10. IRFs to cash deposit velocity-related shock with different default probabilities.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

5.2. Extensions

As mentioned, for robustness, we consider two different scenarios (in essence, solving two sets of slightly different models again), where: i) default probability becomes material to the dynamic system due to costly collateral recovery, and we are facing an increase in default rates; and ii) instead of direct LPR-setting as a policy tool, the central bank sets LTV ratio instead. We note that the earlier findings with regard to the cyclical implications of CBDCs are qualitatively robust to these changes in model specifications.

5.2.1. Default probability and costly collateral recovery

We introduce a specification where only a fraction, $\phi \in (0,1)$, of the pledged collaterals are recovered (perhaps due to costly recovery) by the commercial bank. This then alters the break-even condition of the commercial bank to become:

$$(1-\varphi_t)\left(1+i_t^L\right)L_t + \phi\varphi\varkappa_t\mathbb{E}_tP_{t+1}^H H_t = \left(1+i_t^D\right)\left(D_t+J_t^{CB}\right),$$

and the resulting interest spread, previously of (25), would then contain the exogenous probability of default (it no longer cancels out after the collateral constraint is substituted in):

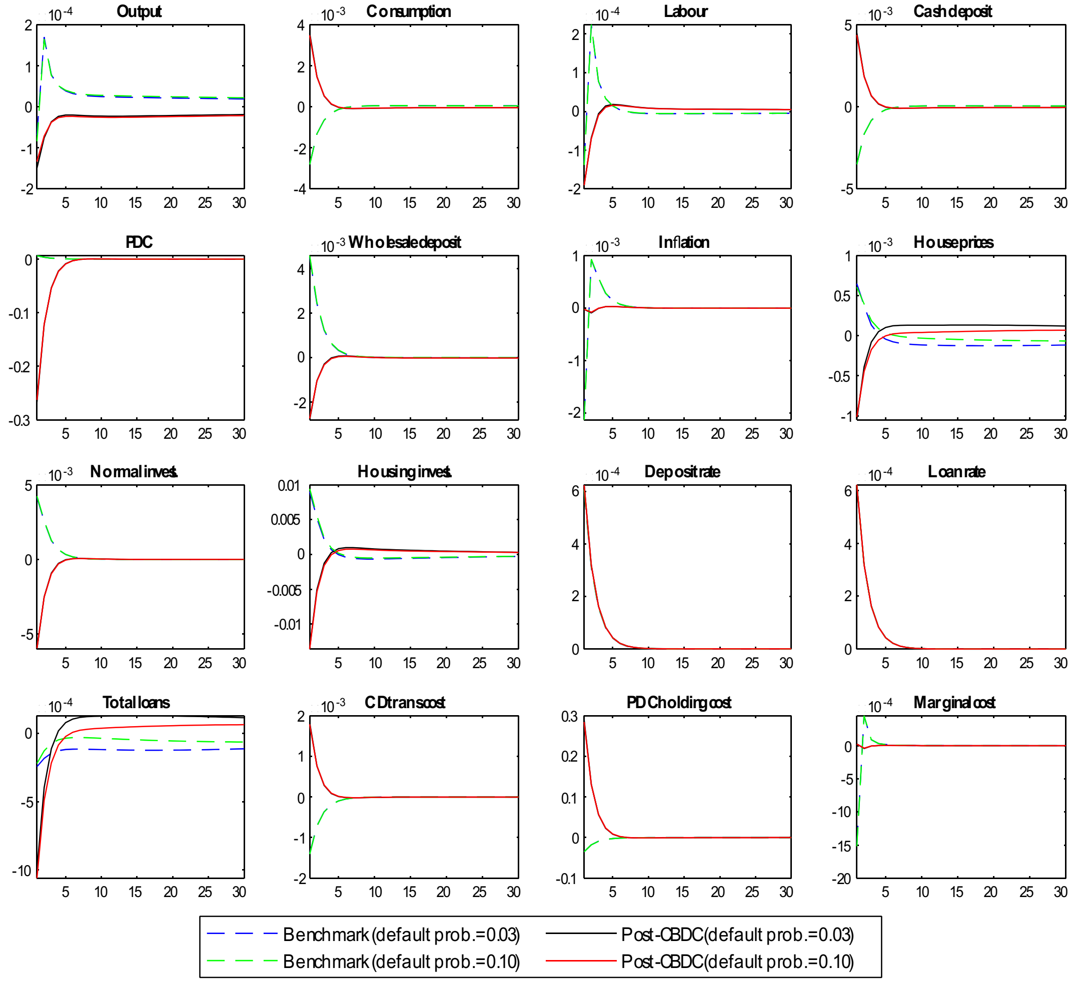

Fig. 11. IRFs to LPR shock with different default probabilities.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

$$\frac{[1-(1-\phi)\varphi](1+i_t^L)}{(1+i_t^D)} = \frac{(D_t + J_t^{CB})}{L_t}. \tag{38}$$

In this scenario, we consider the rollout of CBDC to be taking place in both an economy with a moderate default rate (similar to the current state in China) and an economy with a high default rate, i.e. for both the pre- and the post-CBDC world, we solve to calibrated versions with non-zero default rate. The former is calibrated at $\varphi = 0.03$, which corresponds to the average NPL ratio of domestic Chinese banks. The latter has $\varphi = 0.10$, which corresponds to the high default rate observed in the pre-banking reform era in the early-2000s.

Figs. 8–11 show the IRFs of the pre- and post-CBDC worlds under two different default probabilities. Qualitatively, with more defaults, all the variables respond the same way as in the case with lower default probability. Quantitatively, there are some differences in certain variables, mainly wholesale deposit and its rate, total loans, and house prices. In response to productivity shocks, with higher default probability, wholesale deposit increases marginally in the pre-CBDC world but declines in the post-CBDC world. Its rate also responds less in the benchmark model but more in the post-CBDC model. Total loans and house prices also react largely with higher defaults in the post-CBDC world. This happens similarly in the IRFs to housing productivity shocks. In terms of the IRFs to the cash deposit velocity-related shock, the differences in reactions are very small. Total loans and house prices react largely with higher defaults in both models. With regards to the IRFs to LPR shock, there are no noticeable differences except in house prices and total loans. In summary, we therefore see that, while in a overall cyclicality does increase in the high default-rate world, the " amplifying procyclicality" properties in a post-CBDC world remain.

5.2.2. Alternative LTV policy

Second, we consider an alternative world where there is no explicit/direct setting of the LPR rate, but instead a "LTV ratio as the

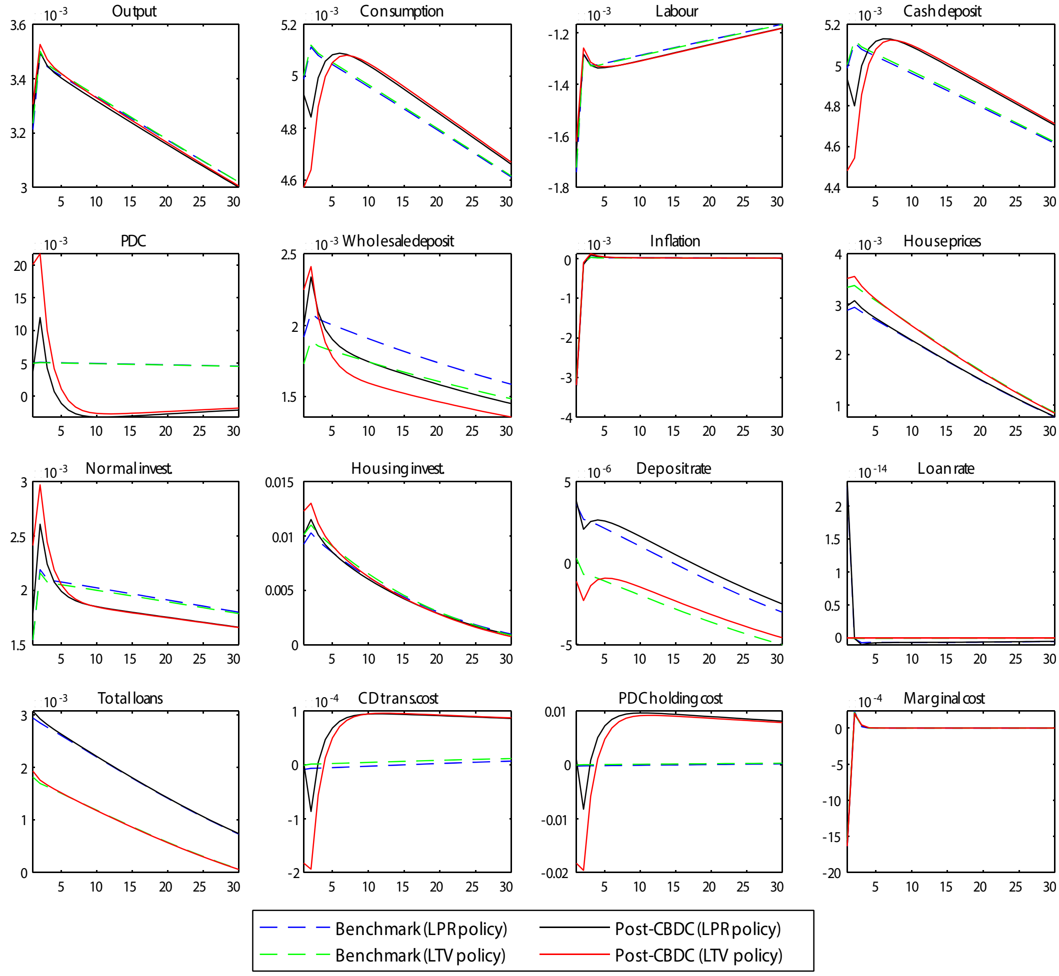

Fig. 12. IRFs to productivity shock under LTV policy.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

policy variable" setting. Specifically, we let the LPR equation be solved entirely endogenously based on the demand theory,

$$1+i_t^L = \left(1+\tilde{i}^L\right)\left(\frac{l_t}{l_{t-1}}\right)^{\nu_2}. \tag{39}$$

Instead, we modify the collateral constraint into a dynamic version, where a time-varying LTV ratio is determined using (40) below, following Rubio and Yao (2020):

$$\varkappa_t = \tilde{\varkappa}\left(\frac{b_t}{\tilde{b}}\right)^{-\varphi_b}\left(\frac{GDP_t}{\widetilde{GDP}}\right)^{-\varphi_y}\varepsilon_t^{LTV}, \tag{40}$$

where $\tilde{\varkappa}, \tilde{b}$ and $\widetilde{GDP}$ are the steady-state values of the LTV ratio, total government borrowings, and GDP respectively. ε_t^{LTV} is the LTV policy shock.

Figs. 12–15 show the IRFs of the pre- and post-CBDC worlds under the two different policy regimes. Again, qualitatively, with LTV policy, all the variables respond in largely similar patterns as in the case of the benchmark LPR-setting world. Therefore, qualitatively similar policy implications are found in terms of the procyclicality of CBDC, and its potential policy complementarity with the loan market regulations. Quantitatively, there are some differences in certain variables when we evaluate the differences between the two IRFs in response to a productivity shock, but very slight differences in the IRF in response to the cash deposit velocity-related shock. As such, our qualitative policy implications remain consistent in this alternative specification of the model too.

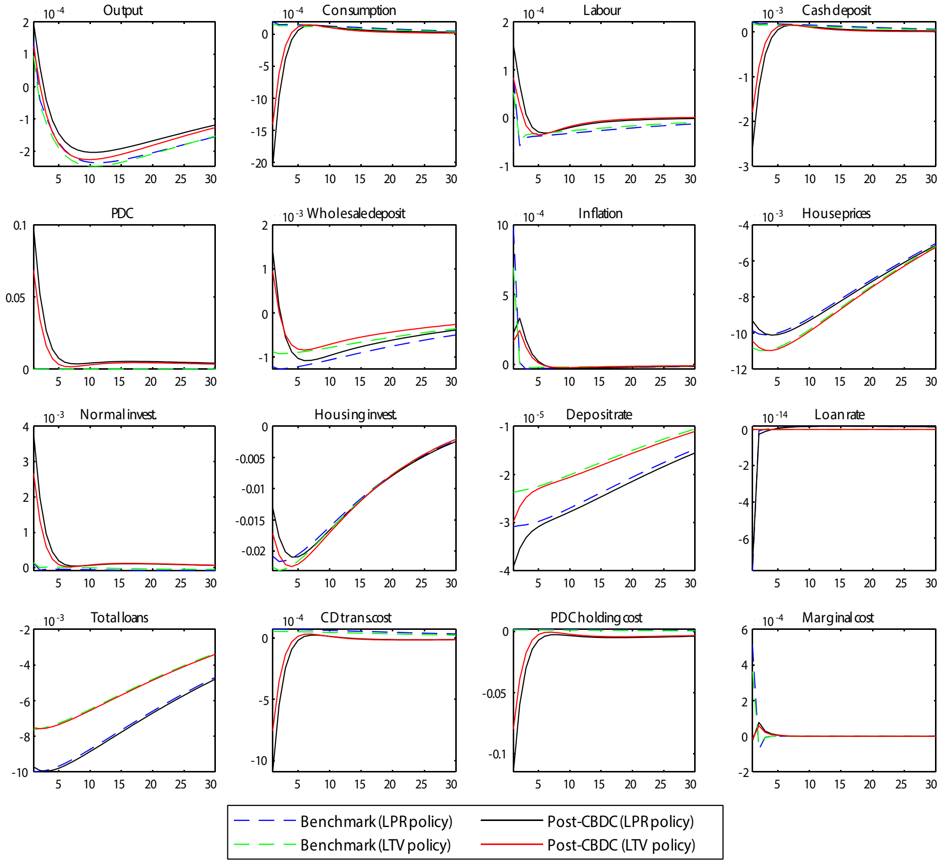

Fig. 13. IRFs to housing productivity shock under LTV policy.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

5.3. *Optimal policy design*

Due to its novelty and lack of precedents in the existing literature, as well as to minimize computational complexity, we approach the optimality search sequentially (using a numerical grid search method), by first attempting to pin down an optimal design for the LPR policy function (30). It is noted that we implement an optimality search for **both** pre-CBDC and post-CBDC world, based on the policy tools available for the Central Bank in either world.

First, in the pre-CBDC world, we start off by searching for an optimal value for the elasticity with respect to loan growth, ν_1, in (30) that maximizes the welfare function in (37), holding the M2 growth rule at its benchmark Bayesian-estimated form. We arrived at a corner solution for the policy parameter, $\nu_1 = 0$, which indicates that an LPR reaction rule to credit expansion is not optimal. Second, we therefore consider a different LPR reaction rule, as in the form of (32), holding again the M2 growth rule's parameters at the Bayesian-estimated values. We find the interior optima for the policy elasticities to be $o_H = 0.052$, and $o_K = -0.100$, i.e. it might be better for the PBOC to set its LPR to be procyclical to housing market growth but anti-cyclical to the growth of nominal physical capital stock in the economy. Third, we turn our attention to the post-CBDC world and implement the optimality search for the policy parameters in (33), holding the M2 growth rule at the benchmark form and the CBDC rate to be at the simple discounted rate (from the wholesale deposit rate). We obtain interior optima of $o_H = 0.046$, $o_K = -0.108$, and $o_{CD} = 0.461$. The latter essentially implies that, in the post-CBDC world any LPR-rate reaction function ought to add an extra mandate that reacts to the growth of CBDC stock. In other words, instead of targeting loan growth, a more efficient policy function is for the Central Bank to determine LPR based on the housing market stabilization mandate, while reducing LPR when the capital asset market is in a bearish state. Of course, in the post-CBDC world, the LPR setting would have to react procyclically to the growth of CBDC stock too. All the results discussed are summarized in Table 7.

Next, having pinned down the optimal form of the LPR reaction function in Table 7, we turn our attention to searching for optimal monetary policy in the post-CBDC world [both in terms of the conventional M2 growth rule (29), and eventually a CBDC interest-rate reactionary rule]. These results are summarized in Table 8. The second column in Table 8 presents the default policy parameter values for the M2 growth rule, as well as the default CBDC policy rule (being set at a discount of the wholesale deposit rate). First, we perform a conditional grid search only for the two parameters in the M2 growth rule for this post-CBDC world, holding the CBDC policy rule at

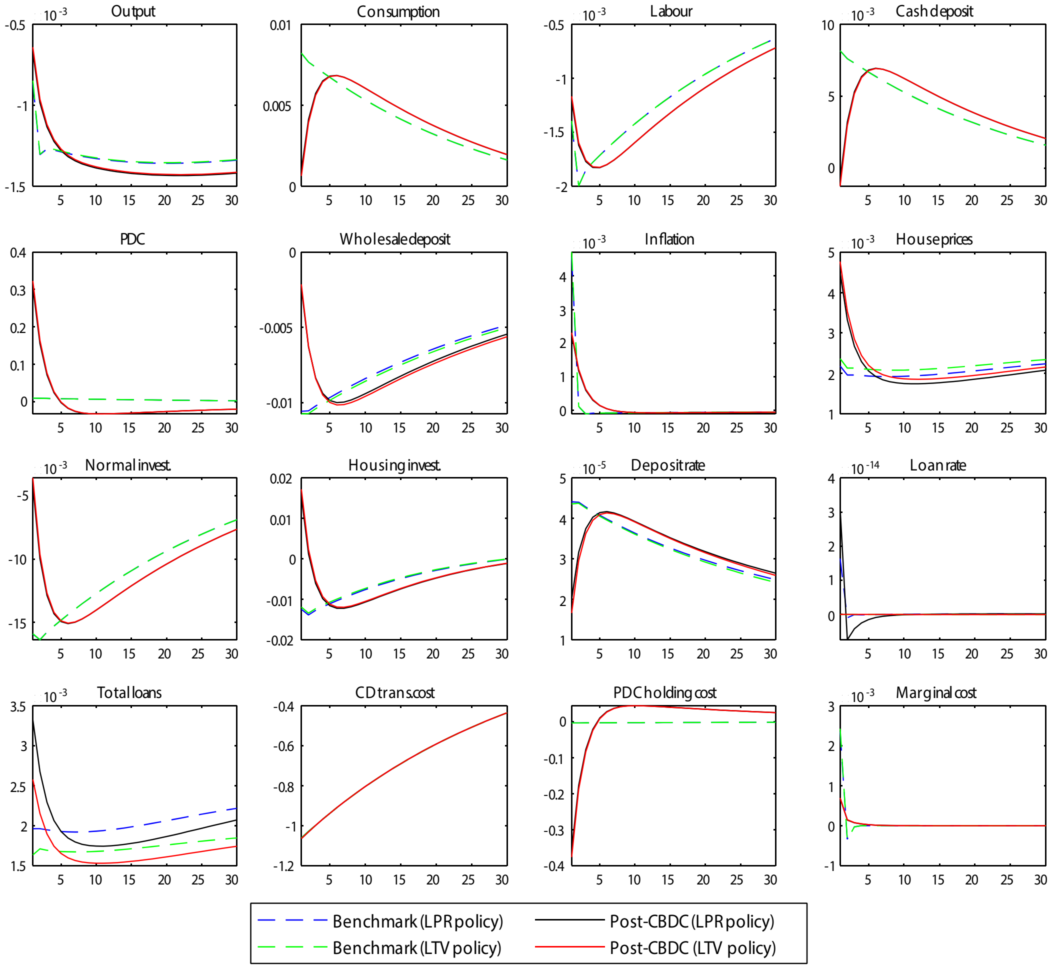

Fig. 14. IRFs to cash deposit velocity-related shock under LTV policy.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

the discounted rate and the LPR reaction function at the optimal form of (33) obtained earlier. We obtain $\nu_1^m = 0.00$ and $\nu_2^m = 0.19$ (as listed in the third column in Table 8), i.e. only the output stabilization mandate yields an interior optimal policy elasticity. However, this regime would improve welfare by 1.35% from the initial baseline. After that, instead of keeping the CBDC rate merely at a discount, we consider the Taylor rule-style function of (34) too and perform a computational-intensive joint search for all 4 policy parameters $(\nu_1^m, \nu_2^m, \kappa_1, \kappa_2)$, holding the LPR reaction function at the optimal form. The results are summarized in the fourth column in Table 8. We observe that the traditional M2 growth rule loses its mandate on output and price stabilization. Instead, optimal policy parameters of $\kappa_1 = 0.930$, $\kappa_2 = 1.732$ are identified for the CBDC policy rule. In this regime, the welfare gain with respect to the initial baseline is 2.71%, which outperforms the 1.35% gain when CBDC interest is set merely at a discount. This suggests that only one form of active monetary policy should be used after the full implementation of CBDC, even if both the cash deposit and CBDC were to exist concurrently in the Chinese economy.

6. Concluding remarks

In recent years, the financial system in China has witnessed two major policy changes: (i) an 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 deposit and digital currencies, both being used as payment options by households for consumption. The former is subject to a velocity-related transaction cost, but the digital currencies are not. 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 PDC, albeit with a significant holding/access cost due to the direct trading using Chinese Yuan within China being restricted since 2018.

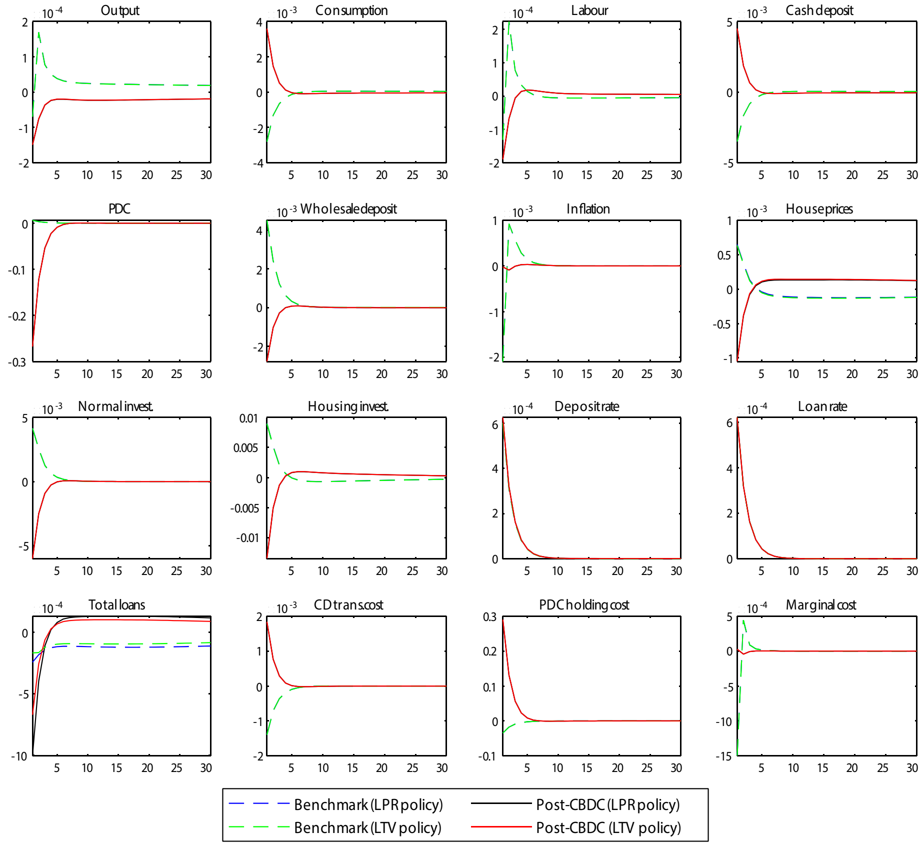

Fig. 15. IRFs to LTV shock under LTV policy.
Note: The y-axis represents the percent deviation from the steady state.
The numbers on the x-axis are measured in quarters.

Table 7
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

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, 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. Moreover, given that the optimal policy combination of LPR reaction rule (that reacts to the growth in CBDC stock, housing, and physical capital markets) and Taylor-style CBDC interest rate rule is welfare-superior to the policy cocktail with conventional M2 growth rule in place of the latter (and in this case, CBDC rate is merely set at a discount to wholesale deposit rate), we propose that only one form of active monetary policy should be used after the full implementation of CBDC.

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

Table 8
Optimal monetary policy.

Money Supply (M2) Growth Rule and CBDC Policy Function				
	Benchmark model	Optimal policy parameters		
Monetary policy function	Bayesian-estimated policy parameters	Conditional search	Joint-search of 4 parameters	Welfare gain
M2 growth rule				1.35%
Elasticity: inflation gap	−0.720	0.000	0.000	
Elasticity: output gap	0.249	0.190	0.000	
CBDC policy rule				2.71%
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 optimal form identified in Table 7.
Welfare gain refers to the total steady-state welfare gain (in percentage of permanent consumption) of switching from the original estimated model to the models in columns 3 and 4.

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 deposits and CBDC should be implemented. This, along with other CBDC considerations, notably the other systemic risks associated with maintaining a DLT system for an economy with a nearly 1.4 billion population, are potential topics. Lastly, we also recognize that we cannot answer every question with regard to CBDC, especially the permanent quantitative differences following its roll-out. For this, the model in studies focusing more on deterministic shocks, such as Barrdear and Kumhof (2016, 2022), would fare better. Instead, we provide more food for thought in the context of qualitative differences between the current and the post-CBDC world, while attempting to identify some potential optimal CBDC policy designs for China. These are our limitations, which we believe future researchers can definitely improve on.

CRediT authorship contribution statement

King Yoong Lim: Conceptualization, Writing – original draft, Methodology, Writing – review & editing, Validation. **Chunping Liu:** Data curation, Methodology, Software, Writing – review & editing, Validation. **Shuonan Zhang:** Data curation, Methodology, Software, Writing – review & editing.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary appendix to this article can be found online at https://doi.org/10.1016/j.ememar.2024.101108.

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