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The external financial spillovers of CBDCs

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ABSTRACT

We set up a DSGE model to study the macroeconomic consequences of a foreign central bank digital currency (CBDC) available to residents in a small open economy. We find that a gradual and permanent increase in the domestic households' preferences toward the foreign CBDC leads to a structural reduction in economic activity, especially if the CBDC is designed to be similar to domestic deposits. Imposing capital flow management measures on outflows, relaxing macroprudential policy, or selling foreign reserves can smooth the transition. A Taylor rule that targets PPI inflation is more effective in limiting the disruptive effects than a CPI targeting or an exchange rate peg. A central bank's liquidity facility available to commercial banks is able to avoid the long-run GDP loss, at the cost of a larger short-run consumption fall. We also show that an economy with a large stock of foreign CBDC is better shielded from exogenous increases in the interest rate on foreign debt, if the CBDC remuneration remains constant.

1. Introduction

In recent years central banks around the world have been increasingly working on projects regarding the feasibility, the benefits, and the costs of issuing a retail central bank digital currency, henceforth CBDC: a retail CBDC is defined as a liability of the central bank, denominated in the national unit of account, whose access is electronic and available also to households and non-financial firms (BIS, 2021). A retail CBDC would fill a gap, as households and non-financial firms have typically access to two forms of money: a physical liability of the central bank (cash) and an electronic liability of the banking sector (deposits). Introducing a CBDC may have major macroeconomic and financial implications: this has spurred a growing academic research (see Auer et al., 2022 for a literature review) and a lively debate in policy institutions such as the IMF and the BIS (Soderberf et al., 2022; BIS, 2021).

The major central banks in the world are examining the introduction of a CBDC or have already launched a pilot digital currency. The Fed is in a research stage, exploring the implications of, and options for, issuing a CBDC (Fed, 2022). After the conclusion of the investigation phase, in November 2023 the ECB has started the preparation phase for the digital euro, with the goal of laying the foundations for its potential issuance (ECB, 2023). The PBOC is running a pilot test in different regions. According to PBOC intentions, the digital Yuan should pay no interest, anonymity should be guaranteed for low value transactions, while traceability is preserved for high value transactions. At this stage, the digital Yuan, similarly to other CBDC projects, is available to Chinese residents and to foreign residents that temporarily travel to China (PBOC, 2021).[1] The possibility of making retail CBDCs available also to non-residents is one of the options considered in the current policy debate in order to address the existing frictions in cross-

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[1] Other smaller countries and areas have already launched a CBDC (e.g. Nigeria, the Bahamas, and the Eastern Caribbean Currency Union).

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border payments (BIS et al., 2022). Should a large economy's CBDC be available also to non residents, other countries may experience relevant spillover effects, such as capital outflows, currency depreciation, and financial distress. In this paper we address these issues, analyzing the financial implications for a small open economy of a foreign retail CBDC available to domestic households.

To this purpose, we set up a DSGE model for a small open economy. We assume that households can invest in three liquid assets: cash, which is issued by the domestic central bank, deposits, which are issued by domestic commercial banks, and a CBDC, which is issued by a foreign central bank. Households enjoy utility from these assets, arising from liquidity services as in Sidrauski (1967), and disutility, due to the loss of security or anonymity, as in Agur et al. (2022).[2] To explore the financial stability consequences of the foreign CBDC, the model features a frictional banking sector à la Gertler and Karadi (2011): we assume that domestic banks use domestic deposits, foreign deposits, and their own net worth to grant loans to domestic firms. As standard in the New Keynesian literature, prices are sticky (Rotemberg, 1982). In the main specification, the model is calibrated to a prototypical emerging market economy (EME) with a flexible exchange rate regime and a soft inflation targeting, whose parameter values are selected following the quantitative model of the IMF Integrated Policy Framework (IPF, Adrian et al., 2021).[3] These economies are typically not dollarized and the local banking sector relies mostly on deposits collected from resident households. In the analysis we will also consider alternative monetary policy rules, like a PPI targeting and an exchange rate peg.

We distinguish two types of foreign CBDC designs, cash-like and deposit-like, which differ in the following features. First, while the cash-like CBDC is anonymous but not secure, the deposit-like CBDC is secure but not anonymous: these features affect the parameters of the disutility function. Second, when we simulate positive CBDC demand shocks, under a cash-like CBDC we assume a simultaneous negative cash demand shock. Under a deposit-like CBDC, we assume a simultaneous negative deposit demand shock. For most of the analysis we consider a CBDC with no remuneration; for some exercises we relax this assumption, considering a positive remuneration, both constant and time varying. Instead, we do not try to model the digital nature of CBDC. *De facto*, in our framework a CBDC is a foreign asset yielding liquidity services, similar to foreign cash or to foreign-currency deposits held in foreign banks. What we do want to model is the increased availability of a liquid foreign asset for domestic households, which can be perceived as a close substitute for domestic cash or for domestic deposits. Indeed, we see a foreign CBDC as a technology that allows domestic households to have an easy access to foreign liquid assets. Domestic households may respond by reducing their holding of domestic liquid assets. What are the macroeconomic and financial implications of the availability of a new foreign liquid asset is exactly the research question of the paper.

We carry out the following exercises. First, we simulate a transition toward an economy with a permanently higher preference for the foreign CBDC, both in the cash-like and in the deposit-like scenario. We assess the role of the following policy instruments: capital flows management measures (CFMs) on inflows and outflows, modeled as a tax/subsidy on foreign deposits and CBDC, respectively; macroprudential measures (MPMs), modeled as a tax/subsidy on the net worth of the banking sector; foreign exchange interventions (FXIs), modeled as purchases/sales of foreign bonds by the domestic central bank; two other monetary policy frameworks, such as a soft PPI inflation targeting and an exchange rate peg; and a central bank's liquidity facility available to banks. Some of these policy tools are of particular interest given that they are part of the IPF (Basu et al., 2020; Adrian et al., 2020; Adrian et al., 2021) and the BIS Macro-Financial Stability Framework (MFSF, Cavallino and Hofmann, 2022). Second, we analyze how the economy responds to an increase in the interest rate on foreign deposits, comparing scenarios with or without the foreign CBDC, and with or without a CBDC remuneration.

Our first result shows a negative aspect of the foreign CBDC. We find that the transition toward an economy with a permanently higher preference for the foreign CBDC leads to a structural output drop in the deposit-like scenario. In this case, households strongly reduce their deposit demand, the deposit rate rises, so does the rate on loans, crowding out lending. Banks in part replace domestic with foreign deposits: capital inflows increase, partially offsetting the higher capital outflows resulting from investment in the foreign CBDC. The currency depreciates, as households are increasing the demand for a foreign asset – the CBDC – inducing a reduction in the value of the domestic currency. The currency depreciation raises the cost for banks of paying back foreign deposits, denominated in the foreign currency. The reduction in the price of capital, as a result of a lower firms' capital demand, and the higher borrowing costs for banks trigger the financial accelerator, amplifying the credit spread and the fall in production in the short run. Production remains permanently at a lower level, as deposit and lending rates are higher in the new steady state, discouraging investment demand. In the cash-like case, the fall of deposits is smaller, as households also reduce domestic cash, when their preference for the CBDC is higher: the deposit rate rises by less and only in the short run, with milder consequences for the banking sector.

The second result is partially reassuring. We show that easing MPMs, tightening CFMs on outflows, or selling foreign reserves dampen the disruptive effects of the transition in the deposit-like scenario. Easing MPMs provides banks with more net worth, persuading depositors that the banking sector is solid, thus mitigating the rise in the credit spread. CFMs on outflows reduce the demand for the foreign CBDC, smoothing the transition. Selling foreign reserves contains the currency depreciation, yielding two benefits: paying back foreign deposits is less expensive; inflation rises by less, requiring a milder monetary tightening. We also find that tightening CFMs on inflows is costly in terms of short-term output because banks need foreign deposits, in order to compensate the reduction in domestic deposit demand. Pegging the exchange rate is also costly, as it would require a large monetary tightening. A soft PPI inflation targeting, as opposed to a soft CPI inflation targeting, is more effective in reducing the negative effects of the

[2] It is important to stress that we model the CBDC as a digital and liquid asset, given our interest in financial stability implications of foreign CBDCs. In this respect, we are ignoring the role of CBDCs in currency substitution, which is the focus, for instance, of the analysis in Ikeda (2020), who is more interested in the consequences of foreign CBDCs for monetary policy independence.

[3] For soft CPI inflation targeting we mean a Taylor rule that responds to CPI inflation and output growth.

foreign CBDC, as it requires a lower increase in the nominal rate during the transition. Moreover, we also show that a central bank's liquidity facility available to banks is able to avoid the long-run GDP loss, at the cost of a larger short-run drop in consumption.

Our third result shows a positive aspect of the foreign CBDC, with a caveat. If domestic households hold a relatively high stock of foreign CBDC, the economy is better shielded from increases in the interest rate on foreign debt. In this case, foreign CBDC has a role similar to FX reserves: when the interest rate on foreign debt is higher and the CBDC is not remunerated (or its rate is constant), households sell the foreign CBDC and increase the investment in domestic deposits, which become more remunerative given the higher supply from domestic banks. This improves the stability of the banking sector, ultimately attenuating the fall in output. However, should the CBDC rate also increase, households would invest more in CBDC and less in domestic deposits, amplifying the negative effect of the foreign interest rate shock.

Related literature. Our paper is related to the literature studying the macroeconomic consequences of CBDCs.[4] Most of the papers in this research area focus on the domestic implications of the country issuing the CBDC. Some papers find that the introduction of CBDC could bring benefits, such as reducing the monopolistic power of banks (Andolfatto, 2021), decreasing the quantity of defaultable debt (Williamson, 2022a; Barrdear and Kumhof, 2022), having a more flexible monetary instrument (Davoodalhosseini, 2022). Agur et al. (2022) show that the design of CBDCs has important consequences if network effects affect the choice of payment instruments: a CBDC that closely competes with deposits may induce bank disintermediation, depressing both lending and output (a view shared also by Piazzesi and Schneider, 2022), while a cash-like CBDC may lead to the disappearance of cash, which is detrimental for the welfare of households with strong preferences toward cash. Similarly, Assenmacher et al. (2021) and Burlon et al. (2022) find that the risk of bank disintermediation can be minimized by a central bank when the CBDC remuneration and/or quantity restrictions are chosen properly. Williamson (2022b) argues that CBDCs tend to encourage banking panics, in part because panics are less disruptive when a CBDC is available. Keister and Sanches (2023) assess the trade off between the risk of bank disintermediation and the higher efficiency in payments. Other authors (Brunnermeier and Niepelt, 2019; Niepelt, 2020a; Niepelt, 2020b) claim that as long as CBDC and deposits are perfect substitutes, an equivalence result holds: central banks can inject liquidity in the banking system, compensating banks for the reduction in deposits, without altering the equilibrium allocation of capital and consumption.

Some papers have explored the international macroeconomic implications of CBDCs. The literature has identified different threats to the independence of monetary policy in small open economies that have access to a foreign CBDC. A first threat is currency substitution (Ikeda, 2020): firms in small open economies might find it convenient to set domestic prices in foreign-currency units, thus reducing the effectiveness of monetary policy. Monetary policy autonomy could be threatened also because a foreign CBDC might increase the international linkages, amplifying the spillover effects of foreign shocks (Ferrari Minesso et al., 2022). Using a similar argument, Benigno et al. (2022) show that if two countries invest in the same global cryptocurrency, their economies tend to become more synchronized, constraining their monetary policy. In such situation, Cova et al. (2022) find that the issuance of a domestic CBDC allows the central bank to stabilize macroeconomic conditions in the presence of shocks to the demand or supply of global stablecoins. More germane to our topic, Popescu (2022) shows that a foreign CBDC acting as an international safe asset can increase the risk of financial disintermediation in the domestic banking sector of a small open economy, using a model of bank runs. Kumhof et al. (2023) estimate a two-country DSGE model, finding that issuing a CBDC brings large benefits, by reducing the share of defaultable debt, by decreasing monetary frictions, and distortionary taxation.

We contribute to this growing literature focusing on a country that imports the CBDC from abroad, without controlling its outstanding stock or the interest rate. This is not merely an intellectual exercise, as the main central banks in the world are all studying the possibility to issue a digital currency. To the best of our knowledge, there are two papers that specifically focus on the CBDC recipient country, Ikeda (2020) and Popescu (2022). Relative to the former, we are more interested in the financial implications of a foreign CBDC, as opposed to currency substitution and the potential loss of monetary independence. Relatively to the latter, we use a fully-fledged general-equilibrium model, as opposed to a partial-equilibrium model of bank runs, in order to carry out dynamic simulations. While also Ferrari Minesso et al. (2022) study the international spillover effects of a CBDC, they mainly focus on how a CBDC alters the transmission mechanisms of shocks, without analyzing the transition or the effectiveness of domestic policy instruments.

Finally, our work is related to the IMF IPF and the BIS MFSF (Cavallino and Hofmann, 2022) as we assess how policy makers can use different policy tools (monetary policy, MPMs, CFMs, FXIs, central bank's liquidity) to address a shock to external financial conditions.

The rest of the paper is organized as follows. Section 2 describes the model deriving its equilibrium conditions. In Section 3 we carry out the simulations of the model under alternative scenarios. In Section 4 we perform a sensitivity analysis. Section 5 concludes.

2. The model

We use a DSGE framework for a small open emerging economy. In addition to choosing parameters tailored for an emerging market, the model exhibits two features that are typical of emerging countries: foreign debt is denominated in foreign currency (the "original sin"); import and export prices are invoiced in foreign currency (the dominant currency paradigm, Adler et al., 2020).[5]

[4] See De Bonis et al. (2021) for an introductory reading on the reasons behind the issuance of a CBDC, and its pros and cons.

[5] Another typical feature of emerging markets is the presence of an occasionally-binding collateral constraint that limits borrowing from the rest of the world (Mendoza, 2010). In our model, both domestic and foreign depositors impose a collateral constraint to the banking sector. For the sake of simplicity, in our model the collateral constraint is always binding.

The model works as follows. Households invest in three types of liquid assets: cash, issued by the domestic central bank; domestic deposits, issued by resident commercial banks; and a foreign CBDC, issued by a foreign central bank. These assets yield utility to households and they are imperfect substitutes. Households can also invest in domestic bonds, issued by the local government. They supply labor to domestic firms and consume a bundle of domestic and foreign goods; the price of the latter are invoiced in foreign currency. A domestic final-good firm produces a domestic good using a bundle of differentiated intermediate goods, and sells it to households, capital producers, and the government. Similarly, a foreign final-good importer assembles the intermediate goods produced by domestic intermediate-good firms and sells the resulting imported final good to foreign households: from the point of view of the domestic economy, these are exports.[6] Intermediate-good firms operate in monopolistic competition and are subject to price adjustment costs. They sell the good to the final good firms, both domestic and foreign: in domestic markets the price is invoiced in domestic currency, in foreign markets the price is invoiced in foreign currency. These firms produce their good using domestic labor and domestic capital. The latter is provided by capital producers and is financed by borrowing from banks. Banks are modeled as in Gertler and Karadi (2011): they collect deposits from domestic and foreign households, and lend resources to domestic firms.[7] The central bank adopts a flexible exchange rate regime and uses a Taylor rule to stabilize CPI inflation. We also analyze a broad range of other policy instruments: macroprudential measures; capital flow management measures on inflows and outflows; foreign exchange interventions; Taylor rules targeting the exchange rate or PPI inflation; central bank's loans to banks.

To summarize, compared to Gertler and Karadi (2011), we add an open economy dimension, assuming that the domestic economy trade goods and assets with the foreign economy. In particular, we assume that domestic banks can also raise funds from foreign households and from the local central bank. In order to give a role to the foreign CBDC, we introduce liquid assets (cash, foreign CBDC, and deposits) in the utility function.

In what follows, we thoroughly explain only the features of the model that are less standard, leaving a complete description of the framework in Appendix A.

2.1. Households: intertemporal problem

The representative household maximizes the following utility function:

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\log c_t - \frac{h_t^{1+\varphi_H}}{1+\varphi_H} + \mathcal{L}\left(\frac{D_t}{P_t}, \frac{M_t}{P_t}, \frac{e_t M_t^*}{P_t} \right) \right] \right\}, \tag{1}$$

where c_t is consumption; h_t denotes hours of work in domestic firms; D_t denotes nominal domestic deposits; P_t is the CPI; M_t is cash; M_t^* is foreign CBDC, denominated in the foreign currency; e_t is the nominal exchange rate, defined as the price of one unit of foreign currency in terms of domestic currency (i.e., an increase of e_t indicates a depreciation of the domestic currency); $\mathcal{L}$ is a function that captures both liquidity services offered by deposits, cash, and the foreign CBDC, and costs related to investing in liquid assets. Households can also invest in domestic public bonds B_t, which do not give utility.[8] The inclusion of an extra-utility term for liquid asset holdings captures the characteristics of liquid assets to be immediately available as a means of payments, without the need of modeling explicitly payment transactions, e.g. through a cash-in-advance constraint. Assuming assets in the utility function is a standard feature of DSGE models since Sidrauski (1967), to justify why households invest in assets yielding low (or even zero) returns. This assumption is widely used also by the growing literature studying CBDC in DSGE models (e.g. Ferrari Minesso et al., 2022; Burlon et al., 2022). In Section 2.6, we describe in detail how we specify this function. We further define the following real variables: $d_t \equiv \frac{D_t}{P_t}$, $m_t \equiv \frac{M_t}{P_t}$, $b_t \equiv \frac{B_t}{P_t}$, and $m_t^* \equiv \frac{M_t^*}{P_t^*}$. Household's maximization is subject to the following intertemporal budget constraint:

$$\begin{aligned} c_t + b_t + d_t + m_t + s_t m_t^* = \frac{r_{t-1}}{\pi_t} b_{t-1} + \frac{r_{Dt-1}}{\pi_t} d_{t-1} + \\ + \frac{1}{\pi_t} m_{t-1} + \frac{r_{Mt-1}^*}{\pi_t^*} s_t \left(1 - \tau_{t-1}^O\right) m_{t-1}^* + w_t h_t + \Gamma_t - t_t, \end{aligned} \tag{2}$$

where r_t, r_{Dt}, r_{Mt}^* are the nominal gross interest rates on bonds, deposits, and the foreign CBDC, respectively, while the nominal gross return of cash is one; $\pi_t \equiv \frac{P_t}{P_{t-1}}$ and $\pi_t^* \equiv \frac{P_t^*}{P_{t-1}^*}$ are the gross domestic and foreign CPI inflation rates, respectively, and P_t^* is the foreign CPI; $s_t \equiv \frac{e_t P_t^*}{P_t}$ is the real exchange rate; w_t is the real hourly wage; Γ_t denotes profits from domestic firms, capital producers, and banks; t_t is a lump-sum tax; τ_t^O is a tax on foreign CBDC holdings, which could be interpreted as a capital flow management measure (CFM) on outflows. To be as general as possible, in writing the households' budget constraint we have assumed that the foreign CBDC

[6] The distinction between the domestic final-good producer and the foreign importer is necessary given the assumption of dominant currency pricing, which requires market segmentation.

[7] Several papers use the Gertler and Karadi (2011)'s framework in open economy: a non-exhaustive list includes Aoki et al. (2016), Banerjee et al. (2016), Akinci and Queralto (2018), Kitano and Takaku (2020), and Kolasa and Wesolowski (2023).

[8] We are assuming that the foreign CBDC is able to promote financial inclusion of domestic households, allowing them to have a direct access to foreign assets, in line with the objectives of many CBDC projects (BIS et al., 2022). Our results do not change if we allow domestic households to trade also foreign bonds, provided that foreign bonds, as their domestic counterpart, do not enter in the liquidity bundle and they are not perceived similar to the foreign CBDC.

yields a return. However, for most of the analysis, the CBDC net remuneration is set to zero. This assumption is coherent with the existing CBDC projects. The optimality conditions yield the labor supply:

$$h_t^{\varphi_H} = \lambda_t w_t \tag{3}$$

and a Euler equation for each asset:

$$1 = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1} r_t}{\lambda_t \pi_{t+1}} \right) \tag{4}$$

$$1 = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t \pi_{t+1}} \right) + \frac{\mathcal{L}_m \left(d_t, m_t, s_t m_t^* \right)}{\lambda_t} \tag{5}$$

$$1 = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1} r_{Dt}}{\lambda_t \pi_{t+1}} \right) + \frac{\mathcal{L}_d \left(d_t, m_t, s_t m_t^* \right)}{\lambda_t} \tag{6}$$

$$1 = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1} s_{t+1} r_{Mt}^* \left(1 - \tau_t^O\right)}{\lambda_t \pi_{t+1}^* s_t} \right) + \frac{\mathcal{L}_{m^*} \left(d_t, m_t, s_t m_t^* \right)}{s_t \lambda_t}, \tag{7}$$

where $\mathcal{L}_i(\cdot) = \frac{\partial \mathcal{L}(\cdot)}{\partial i}$, with $i \in \left\{ m_t, d_t, m_t^* \right\}$, denotes the marginal extra-utility of holding asset i and

$$\lambda_t = \frac{1}{c_t} \tag{8}$$

is the marginal utility of consumption. As assets yield utility, the Euler equations feature an additional term ($\mathcal{L}_i$), which captures the additional benefit (or cost) of investing in liquid assets. Without these additional terms, there would be perfect parity conditions between bonds, deposits, and CBDC rates (for instance, we would have $r_t = r_{Dt}$, and cash would be a dominated asset, if the zero-lower bound did not bind). Introducing liquid assets in the utility function allows us to break the parity conditions and to obtain demands for deposits, cash, and foreign CBDC that are increasing in the real rate yielded by these assets.

2.2. Banks

We model banks following Gertler and Karadi (2011), with the following departures. We assume that banks can also borrow from foreign households, issuing foreign-currency deposits; the interest rate on these deposits is an increasing function of the economy's external debt. These features aim to better capture the financial sector of an emerging country. Moreover, we also assume that banks have access to a liquidity facility of the central bank.

There is a continuum of banks indexed by j. Each bank j features the following balance sheets:

$$f_t(j) = d_t(j) + s_t d_t^*(j) + d_{Ct}(j) + \left(1 + \tau_t^N\right) n_t(j), \tag{9}$$

where $f_t(j)$ denotes loans of bank j to domestic firms, in CPI terms; $d_t(j)$ represents domestic deposits held in bank j; $d_t^*(j)$ denotes foreign deposits expressed in terms of the foreign CPI; $d_{Ct}(j)$ denotes a liquidity facility of the central bank (in CPI terms); $n_t(j)$ is bank j's net worth; τ_t^N is a subsidy/tax on net worth, that can be interpreted as a macroprudential measure (MPM), as in Gelain and Ilbas (2017): a positive (negative) τ_t^N induces banks to accumulate (reduce) net worth. For simplicity, we assume that banks do not invest in domestic central bank's reserve, as in Gertler and Karadi (2011). Analogously, we assume that banks do not hold the foreign CBDC.[9] Domestic firms borrow from banks to finance their capital expenditures $q_t k_t(j)$, where k_t denotes capital and q_t is its price. It holds: $f_t(j) = q_t k_t(j)$.

We assume that banks do no distribute dividends, until they exit from the market (which happens with probability $1 - \chi$, in every period). Conditional on surviving, the net worth of bank j is equal to profits, i.e. lending revenues minus borrowing costs:

$$n_{t+1}(j) = r_{Bt+1} q_t k_t(j) - \left[\frac{r_{Dt}}{\pi_{t+1}} d_t(j) + \frac{r_{Ct}}{\pi_{t+1}} d_{Ct}(j) + \frac{\Xi_t r_t^* \left(1 + \tau_t^I\right)}{\pi_{t+1}^*} s_{t+1} d_t^*(j) \right], \tag{10}$$

where r_{Bt} is the real lending rate; r_t^* is the foreign interest rate; r_{Ct} is the nominal rate on the central bank's liquidity facility; τ_t^I is a tax on foreign deposits, that can be interpreted as a CFM on inflows; Ξ_t is an endogenous risk-premium:

$$\Xi_t = \bar{\Xi} \exp\left[\kappa_Z \left(d_t^* - \bar{d}^* \right) \right], \tag{11}$$

where d_t^* denotes aggregate foreign deposits. The larger the gap between foreign deposits and the initial steady-state level $\bar{d}^*$, the higher the risk-premium banks pay to foreign investors. This assumption is necessary to make the model stationary (Schmitt-Grohé and Uribe, 2003) but it is also economically meaningful given that countries that are highly indebted with the rest of the world are more likely to pay higher interest rates. As shown below, this assumption implies that the currency premium is an increasing

[9] Unless we assume some additional frictions or a CBDC benefit for the banking sector, the foreign CBDC would be a dominated asset for banks, as it would yield a lower return compared to domestic loans.

function of foreign debt. This is also a feature of the models in Gabaix and Maggiori (2015), Fanelli and Straub (2021), and Itskhoki and Mukhin (2021), where the risk premium is rigorously microfunded.[10]

Following Gertler and Karadi (2011), bankers can divert a fraction θ of their assets. Depositors impose an incentive compatibility constraint, to be sure that the benefit to divert assets is not larger than its cost, given by the value of the bank $V_t(j)$:

$$V_t(j) \geq \theta q_t k_t(j). \tag{12}$$

Gertler and Karadi (2011) show that the leverage ($\phi \equiv \frac{q_t k_t(j)}{n_t(j)}$) is constant across banks and it is an increasing function of the marginal value of investing in loans, which in turn positively depends on the credit spread $r_{Bt+1} - \frac{r_{Dt}}{\pi_{t+1}}$: if loans are high relatively to the net worth, depositors require a higher bank's profitability (i.e. a higher credit spread), in order to not withdraw deposits. The credit spread emerges in equilibrium as banks are constrained, so they cannot fully arbitrage between assets and deposits.

As we show in Appendix A.2, the solution of the bank's problem also gives an uncovered interest parity (UIP) condition between domestic and foreign deposits, which reads as follows, up to a first order:

$$\hat{r}_{Dt} - \left[\hat{r}_t^* + \left(\hat{e}_{t+1} - \hat{e}_t\right)\right] = \kappa_Z \bar{d}^* \hat{d}_t^* + \tau_t^I, \tag{13}$$

where a "hat" denotes percentage deviations from steady-state values. The left-hand side features the currency premium, which depends on the stock of foreign deposits and on CFMs on inflows.

2.3. Intermediate-good firms

There is a continuum of firms indexed by i, producing a differentiated domestic input. The production function is the following:

$$y_{Ht}(i) + y_{Xt}(i) = \left(k_{t-1}(i)\right)^{\alpha} \left(h_t(i)\right)^{1-\alpha}, \tag{14}$$

where $y_{Ht}(i)$ denotes output sold to the domestic final-good firm, $y_{Xt}(i)$ denotes output exported to the foreign final-good firm. Intermediate-good firms operate in monopolistic competition, so they set prices subject to the demand of final-good firms, and pay quadratic adjustment costs $AC_{Ht}(i)$ and $AC_{Xt}(i)$, whenever they adjust prices with respect to a given benchmark: $\overline{\pi}$ (Rotemberg, 1982):

$$AC_{Ht}(i) = \frac{\kappa_{PH}}{2}\left(\frac{P_{Ht}(i)}{P_{Ht-1}(i)} - \overline{\pi}\right)^2 P_{Ht} y_{Ht} \tag{15}$$

$$AC_{Xt}(i) = \frac{\kappa_{PX}}{2}\left(\frac{P_{Xt}(i)}{P_{Xt-1}(i)} - \pi^*\right)^2 P_{Xt} y_{Xt}, \tag{16}$$

where $P_{Ht}(i)$ is the price set for domestic markets, $P_{Xt}(i)$ is the price set for foreign markets, which is expressed in foreign currency; y_{Ht} and y_{Xt} denote the final-good bundles, P_{Ht} and P_{Xt} denote the prices of these bundles. This assumption ensures that prices in domestic (foreign) markets are sticky in domestic (foreign) currency.

As we show in Appendix A.4, the solution of the profit maximization problem of intermediate-good firms yields a domestic-market and a foreign-market Phillips Curve:

$$\pi_{Ht}\left(\pi_{Ht} - \overline{\pi}\right) = \beta \mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{Ht+1}\left(\pi_{Ht+1} - \overline{\pi}\right)\frac{p_{Ht+1}y_{Ht+1}}{p_{Ht}y_{Ht}}\right] + \frac{\varepsilon_H}{\kappa_{PH}}\left(\frac{mc_t}{p_{Ht}} - \frac{\varepsilon_H - 1}{\varepsilon_H}\right) \tag{17}$$

$$\pi_{Xt}\left(\pi_{Xt} - \pi^*\right) = \beta \mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{Xt+1}\left(\pi_{Xt+1} - \pi^*\right)\frac{p_{Xt+1}y_{Xt+1}}{p_{Xt}y_{Xt}}\right] + \frac{\varepsilon_X}{\kappa_{PX}}\left(\frac{mc_t}{p_{Xt}} - \frac{\varepsilon_X - 1}{\varepsilon_X}\right), \tag{18}$$

where mc_t is the firm's real marginal cost; $p_{Ht} \equiv \frac{P_{Ht}}{P_t}$ and $p_{Xt} \equiv \frac{e_t P_{Xt}}{P_t}$ are the prices expressed in terms of domestic CPI; $\pi_{Ht} \equiv \frac{P_{Ht}}{P_{Ht-1}}$ is PPI inflation in domestic markets, and $\pi_{Xt} \equiv \frac{P_{Xt}}{P_{Xt-1}}$ is PPI inflation in foreign markets; ε_H and ε_X are positive parameters capturing the elasticity of substitution between differentiated goods in domestic and foreign markets.[11]

2.4. Policy

The balance sheets of the central bank read:

$$s_t b_t^* + d_{Ct} + b_{Ct} = m_t, \tag{19}$$

[10] See Yakhin (2022) for an equivalence result between the model of Gabaix and Maggiori (2015), Fanelli and Straub (2021), and a model with a risk premium similar to the specification in equation (11).

[11] Adjustment costs in foreign markets are computed relative to foreign inflation π^*, in order to have zero costs in steady state. This occurs as it holds $\pi_{Xt} = \frac{p_{Xt}}{p_{Xt-1}}\frac{s_{t-1}}{s_t}\pi_t^*$, which implies $\pi_X = \pi^*$ in steady state.

where b_t^* denotes holding of foreign bonds (FX reserves), which yield the same rate of foreign deposits (net of the risk premium); b_{Ct} denotes holding of domestic public bonds. The central bank transfers profits Γ_{Ct} to the government:

$$\Gamma_{Ct} = \frac{r_{t-1}}{\pi_t} b_{Ct-1} + \frac{r_{Ct-1}}{\pi_t} d_{Ct-1} + \frac{r_{t-1}^*}{\pi_t^*} s_t b_{t-1}^* - \frac{1}{\pi_t} m_{t-1}. \tag{20}$$

The government has the following budget constraint:

$$p_{Ht} g_t + \frac{r_{t-1}}{\pi_t} b_{Gt-1} + \tau_t^N n_t = t_t + \tau_{t-1}^O s_t \frac{r_{Mt-1}^*}{\pi_t^*} m_{t-1}^* + \tau_{t-1}^I \frac{\Xi_{t-1} r_{t-1}^*}{\pi_t^*} s_t d_{t-1}^* + b_{Gt} + \Gamma_{Ct}, \tag{21}$$

where g_t denotes public spending in the domestic good, and b_{Gt} denotes outstanding public debt. In the left-hand side of the constraint there are public expenses, which include government consumption, repayment of public bonds, and the macroprudential subsidy. To finance these costs, the government sets lump-sum and CFMs taxes, it issues public bonds, and it uses profits from the central bank. Given the market clearing condition for public bonds $b_{Gt} = b_{Ct} + b_t$, (public bonds are held by the central bank and by households) the consolidated budget constraint of the public sector reads:

$$\begin{aligned} & p_{Ht} g_t + s_t b_t^* + d_{Ct} + \frac{r_{t-1}}{\pi_t} b_{t-1} + \frac{1}{\pi_t} m_{t-1} + \tau_t^N n_t = t_t + \tau_{t-1}^O s_t \frac{r_{Mt-1}^*}{\pi_t^*} m_{t-1}^* + \\ & + \tau_{t-1}^I \frac{\Xi_{t-1} r_{t-1}^*}{\pi_t^*} s_t d_{t-1}^* + b_t + m_t + \frac{r_{t-1}^*}{\pi_t^*} s_t b_{t-1}^* + \frac{r_{Ct-1}}{\pi_t} d_{Ct-1}. \end{aligned} \tag{22}$$

The central bank controls the following instruments:

$$\left\{ r_t, b_t^*, b_{Ct}, d_{Ct} \right\}.$$

We assume that the nominal interest rate is set according to the following Taylor rule:

$$\frac{r_t}{r} = \left(\frac{r_{t-1}}{r} \right)^{\rho_r} \left[\left(\frac{\pi_t}{\overline{\pi}} \right)^{\phi_\pi} \left(\frac{gdp_t}{gdp_{t-1}} \right)^{\phi_y} \right]^{1-\rho_r}, \tag{23}$$

where $gdp_t \equiv p_{Ht} y_{Ht} + p_{Xt} y_{Xt}$ is gross domestic product, expressed in terms of the CPI. In most of the analysis we keep b_t^* and d_{Ct} constant at the steady-state value: in a couple of exercises, we consider the role of FX intervention and of the central bank's liquidity facility in mitigating the effects of an increase in the preference for the foreign CBDC; b_{Ct} is determined by the balance sheets of the central bank, given b_t^* and m_t.[12]

The government controls the following instruments:

$$\left\{ g_t, b_{Gt}, \tau_t^N, \tau_t^O, \tau_t^I, t_t \right\}.$$

We assume that all these instruments but t_t are kept constant in the steady state in most of the analysis, unless is specified otherwise: in particular, we will assess the role of macroprudential policy τ_t^N and of CFMs on inflows and outflows τ_t^O and τ_t^I in mitigating the effects of an increase in the preference for the foreign CBDC. Lump-sum taxes t_t are determined by the government's budget constraint, given all the other instruments.

2.5. Aggregate resource constraint

The aggregate resource constraint of the economy reads:

$$\begin{aligned} & c_t + i_t + p_{Ht} g_t + \frac{\kappa_{PH}}{2} \left(\pi_{Ht} - \overline{\pi} \right)^2 p_{Ht} y_{Ht} + \frac{\kappa_{PX}}{2} \left(\pi_{Xt} - \pi^* \right)^2 p_{Xt} y_{Xt} + s_t \left(m_t^* + b_t^* - d_t^* \right) = \\ & \qquad gdp_t + \frac{s_t}{\pi_t^*} \left(r_{Mt-1}^* m_{t-1}^* + r_{t-1}^* b_{t-1}^* - r_{t-1}^* \Xi_{t-1} d_{t-1}^* \right). \end{aligned} \tag{24}$$

The last equation shows that GDP ($p_{Ht} y_{Ht} + p_{Xt} y_{Xt}$) plus return on net external assets is equal to domestic absorption (consumption, investment, public spending, and price adjustment costs) plus net external investment. There are three financial links between the domestic economy and the rest of the world: the foreign CBDC m_t^*, FX reserves b_t^*, and foreign deposits d_t^*. Defining the trade balance (tb_t) as the difference between exports (xp_t) and imports (mp_t), it is possible to show that:

$$tb_t = s_t \left(m_t^* + b_t^* - d_t^* \right) - \frac{s_t}{\pi_t^*} \left(r_{Mt-1}^* m_{t-1}^* + r_{t-1}^* d_{t-1}^* - r_{t-1}^* \Xi_{t-1} d_{t-1}^* \right).$$

[12] Cash is not directly chosen by the central bank, which sets its net return to 0.

2.6. Calibration

We calibrate the model to a prototypical emerging economy. In our simulations, time periods t correspond to quarters. We first describe the utility function of liquid assets and its parameters, second we explain how we calibrate the remaining parameters.

2.6.1. Utility of liquid assets

We specify the functional form of $\mathcal{L}$ in the utility of households. We assume that it is a combination of three components:

$$\mathcal{L}\left(d_t, m_t, s_t m_t^*\right) = \zeta_L \frac{L_t\left(d_t, m_t, s_t m_t^*\right)^{1-\varphi_L}}{1-\varphi_L} - \zeta_S \frac{S_t\left(m_t, s_t m_t^*\right)^{1+\varphi_S}}{1+\varphi_S} - \zeta_A \frac{A_t\left(d_t, s_t m_t^*\right)^{1+\varphi_A}}{1+\varphi_A}. \tag{25}$$

The first term (L_t) captures the extra-utility households derive from investing in liquid assets. By assuming that assets give utility we aim to capture the following three features, in reduced form: the transaction services of certain types of securities (e.g. to easily exchange CBDC for consumption goods); their liquidity value (e.g. to easily exchange CBDC for other liquid assets, such as cash and deposits); their safety benefits relatively to other riskier securities. We assume the following CES bundle:

$$L_t\left(d_t, m_t, s_t m_t^*\right) = \left[\kappa_{Mt}^{\frac{1}{\epsilon_L}}\left(m_t\right)^{\frac{\epsilon_L-1}{\epsilon_L}} + \kappa_{Dt}^{\frac{1}{\epsilon_L}}\left(d_t\right)^{\frac{\epsilon_L-1}{\epsilon_L}} + \left(\kappa_{Mt}^*\right)^{\frac{1}{\epsilon_L}}\left(s_t m_t^*\right)^{\frac{\epsilon_L-1}{\epsilon_L}}\right]^{\frac{\epsilon_L}{\epsilon_L-1}}, \tag{26}$$

where κ_{Mt}, κ_{Dt}, and κ_{Mt}^* are the time-varying weights measuring household's preferences over the three monetary assets. We follow the literature and we include in the liquidity bundle the most liquid assets, such as cash and deposits, plus the CBDC (see for instance Burlon et al., 2022). Following Agur et al. (2022), we assume that households suffer disutility from loss of both security (S_t) and anonymity (A_t). Security loss is an increasing function of cash, which can deteriorate or be lost. Anonymity loss is an increasing function of deposits, as they are fully traceable. The foreign CBDC can be more similar to cash or to deposits, depending on its design: on the one hand, a cash-like CBDC allows a greater degree of anonymity but it can be stolen and appropriated by hackers (Kahn et al., 2021); on the other hand, a deposit-like CBDC is fully traceable but more secure. Denoting with ψ the degree of similarity between CBDC and cash, we write the security and anonymity loss as:

$$S_t\left(m_t, s_t m_t^*\right) = m_t + \psi s_t m_t^* \tag{27}$$

$$A_t\left(d_t, s_t m_t^*\right) = d_t + (1-\psi) s_t m_t^*. \tag{28}$$

The security and the anonymity loss functions imply that when $\psi > 0.5$ the foreign CBDC is more similar to cash, when $\psi < 0.5$ the foreign CBDC is more similar to deposits. As noted in the introduction with reference to the digital Yuan, the classification of digital currencies according to anonymity vs security criteria reflects the current options and hypotheses on the design of CBDCs.[13] It is important to notice that our specification is sufficiently general to incorporate a variety of foreign financial instruments. On one extreme, the case of a pure cash-like CBDC ($\psi = 1$) with no remuneration ($r_{Mt}^* = 0$) is very close to a foreign fiat currency: in this regard, our framework can be seen as a generalization of standard models employed to study dollarized economies. On the other extreme, when $\psi = 0$ and $r_{Mt}^* > 0$, the CBDC is indistinguishable from a foreign illiquid asset, unless it provides liquidity services ($\kappa_{Mt}^* > 0$). Hence, for intermediate parameter values, our model is able to capture the hybrid nature of (foreign) CBDCs, as these instruments can be interpreted as both an asset and a means of payments.

Given these functional forms, the marginal utilities of assets in equations (4)-(7) read:

$$\mathcal{L}_d\left(d_t, m_t, s_t m_t^*\right) = \zeta_L\left(\kappa_{Dt}\frac{L_t}{d_t}\right)^{\frac{1}{\epsilon_L}} L_t^{-\varphi_L} - \zeta_A A_t^{\varphi_A} \tag{29}$$

$$\mathcal{L}_m\left(d_t, m_t, s_t m_t^*\right) = \zeta_L\left(\kappa_{Mt}\frac{L_t}{m_t}\right)^{\frac{1}{\epsilon_L}} L_t^{-\varphi_L} - \zeta_S S_t^{\varphi_S} \tag{30}$$

$$\mathcal{L}_{m^*}\left(d_t, m_t, s_t m_t^*\right) = \zeta_L\left(\kappa_{Mt}^*\frac{L_t}{s_t m_t^*}\right)^{\frac{1}{\epsilon_L}} L_t^{-\varphi_L} - \zeta_S \psi S_t^{\varphi_S} - \zeta_A (1-\psi) A_t^{\varphi_A}. \tag{31}$$

When we simulate a positive preference for the foreign CBDC (κ_{Mt}^*), we need to specify whether the other weights (κ_D and κ_M) also change. In most simulations, we assume:

$$\tilde{\kappa}_{Mt} = -\psi \tilde{\kappa}_{Mt}^* \tag{32}$$

$$\tilde{\kappa}_{Dt} = -(1-\psi)\tilde{\kappa}_{Mt}^*, \tag{33}$$

where a tilde means a deviation from the initial steady state. This implies that if the CBDC is cash-like ($\psi = 1$), the increase in the preference for the foreign CBDC is associated to a lower preference for domestic cash; if $\psi = 0$ the CBDC is completely akin to

[13] The central role played both by anonymity and security preferences in shaping CBDC demand is also confirmed by a public survey on CBDCs carried out by the ECB (ECB, 2021).

Table 1
Calibrated parameters.

Calibration: parameters

Parameters	Description	Value
β	Discount factor	0.9953
φ_H	Inverse of Frisch elasticity	1
φ_L, φ_S, φ_A	Curvature of MIU	$1, 1, 1$
$\zeta_L, \zeta_S, \zeta_A$	Weight of money utilities	$0.014, 0.0001, 0.0001$
$\kappa_M, \kappa_D, \kappa_M^*$	Weight of means of payments	$0.8, 0.2, 0.0$
ε_L	El. of subst. btw means of payments	1.6
γ, γ^*	Weight of imported and exported good	$0.3, 0.3$
η	El. of subst. domestic vs foreign good	1.5
$\varepsilon_H, \varepsilon_X$	El. of subst. differentiated goods	6
α	Share of capital in production	0.33
δ	Depreciation rate	2.5%
χ	Survival rate of bankers	95%
θ	Fraction of divertable assets	39%
ι	Transfer for new bankers	0.43%
κ_I	Investment adjustment cost	2.85
κ_{PH}, κ_{PX}	Price adjustment cost	157
$\kappa_Z, \bar{\Xi}$	Endogenous risk premium	$0.01, 1.001$
ϕ_π, ϕ_y, ρ_r	Taylor rule parameters	$1.5, 0.0625, 0.82$

deposits, and an increase in the preference toward the CBDC is compensated by an equal reduction of the deposit weight. We also study a liquidity-expansion shock, in which the foreign CBDC increases the liquidity conditions of domestic households, through the increase of κ^*_{Mt}, without implying a reduction in the weight of the other means of payments ($\tilde{\kappa}_{Mt} = \tilde{\kappa}_{Dt} = 0$). We choose a logarithmic utility for the liquidity bundle ($\varphi_L = 1$), as in Alpanda and Kabaca (2020), and a quadratic cost for the security and anonymity loss ($\varphi_S = \varphi_A = 1$). Moreover, following Cova et al. (2022), we set the preference for domestic cash (κ_M) equal to 0.8 and the elasticity of substitution between means of payments (ε_L) equal to 1.6: as Cova et al. (2022), Burlon et al. (2022), and many others, we see these assets as similar securities that households perceive as imperfect substitutes. Setting κ^*_M to 0 in the initial steady state, we calibrate $\kappa_D = 0.2$, so that the weights sum to 1. Using data on a sample of EMEs with a flexible exchange rate, we set ex ante the steady state cash to GDP ratio ($\frac{m}{4gdp}$) to 7.4%, and find ex post $\zeta_L = 0.014$.[14] We calibrate $\zeta_A = \zeta_S = 0.0001$, which is obtained by assuming that the interest rate on bonds is equal to the deposit rate, in the initial steady state. We set the gross nominal return on the foreign CBDC to 1, given current projects are converging on zero-interest CBDCs.

2.6.2. *Other parameters*

We follow the quantitative model of the Integrated Policy Framework (IPF), whose quarterly calibration is based on a sample of 16 EMEs with a floating exchange rate regime (Adrian et al., 2021). We set the annualized domestic and foreign steady-state inflation rates ($4(\pi - 1)$ and $4(\pi^* - 1)$) to 4% and 2%, respectively, which implies $\bar{\Xi} = 1.001$. We set the annualized real domestic and foreign policy rate ($4(r/\pi - 1)$ and $4(r^*/\pi^* - 1)$) to 1.9% and 1.5%, respectively: this implies $\beta = 0.9953$; we calibrate the inverse of the Frisch elasticity (φ_H) to 1; the trade openness parameter and the export shifter (γ, γ^*) are both equal to 0.3. We calibrate the elasticity of substitution between differentiated goods ε_H and ε_X equal to 6. We set the steady-state foreign debt and FX reserves over GDP ratios ($\frac{s \cdot d^*}{4gdp}$ and $\frac{s \cdot b^*}{4gdp}$) equal to 42% and 20%, respectively: this implies $\bar{d}^* = 2.72$ and $b^* = 1.29$.[15] Foreign output is normalized to 1. The steady-state public spending-GDP ratio ($\frac{p_H g}{gdp}$) is equal to 14%, which implies $g = 0.34$. The parameters of the Taylor rule (ϕ_π, ϕ_y) are set to 1.5 and 0.0625. The monetary policy inertia ρ_r is set to 0.82. MPMs, CFMs and the liquidity facility are set to 0. The remaining parameters are absent or not specified in Adrian et al. (2021), and we follow Akinci and Queralto (2018). The survival rate of bankers (χ) is equal to 0.95. The domestic bank leverage in steady state (ϕ) is equal to 5, which implies $\theta = 0.39$. The annualized steady-state lending spread $4\left(r_B - \frac{r_D}{\pi}\right)$ is set to 2%, which implies $\iota = 0.004$. The elasticity of substitution between domestic and foreign goods (η) is set to 1.5. The share of capital in the production function (α) is equal to 0.33. The depreciation rate of capital (δ) is calibrated to 2.5%. The strength of investment adjustment cost κ_I is set to 2.85. Assuming a fraction of firms with sticky prices equal to 84% as in Akinci and Queralto (2018) is equivalent to calibrate the price adjustment cost (κ_{PH}, κ_{PX}) to 157. The risk-premium elasticity with respect to foreign deposits (κ_Z) is calibrated to 0.01, as in Benigno (2009).

Table 1 summarizes the calibrated values for the model parameters, Table 2 reports the steady-state values that are calibrated ex ante.

[14] This is the same sample considered by the IMF Integrated Policy Framework (Adrian et al., 2021).

[15] This implies a foreign-domestic deposit ratio ($\frac{s \cdot d^*}{d}$) of 36%. The reader may be concerned that in EMEs this ratio is much higher: if this was the case, domestic deposits would not be much relevant for domestic banks, which in turn would be less affected from a reduction in domestic deposit demand arising from a stronger CBDC preference. According to IFS data, this ratio is around 20% in EMEs; hence, we are somewhat overestimating the foreign liabilities of the domestic banking sector, which reinforces our main finding.

Table 2
Calibrated steady state (SS) values.

Calibration: steady state

SS Values	Description	Value
$d^*/4gdp_\$$	SS external debt/GDP	42%
$b^*/4gdp_\$$	SS FX/GDP	20%
$p_H g/gdp$	SS public spending/GDP	14%
$m/4gdp$	SS cash/GDP	7.4%
$m^*/4gdp_\$$	SS CBDC/GDP	0.0%
$4sp$	SS annualized domestic spread	2%
ϕ	Domestic bank leverage	5
$4(\pi-1), 4(\pi^*-1)$	Annualized SS inflation	4%, 2%
$4(r/\pi-1), 4(r^*/\pi^*-1)$	Annualized real policy rates	1.9%, 1.5%
$4\left(r_D/\pi-1\right)$	Annualized real deposit rate	1.9%
$4\left(r_M^*-1\right)$	Annualized nominal CBDC rate	0%
d_C	Liquidity facility	0
y^*	Foreign output	1

3. Analysis

In this section, we study the transition toward an economy with a permanent stronger preference for the foreign CBDC, analyzing the effectiveness of a wide set of policy tools. Moreover, we simulate a temporary increase in the foreign interest rate, comparing different scenarios based on the initial stock of the foreign CBDC. In the figures, we plot the following transformations of the variables of the model. Most variables are plotted in percentage deviations from the initial steady state; for instance, in the case of GDP:

$$GDP = 100\frac{gdp_t - gdp_0}{gdp_0},$$

where 0 is the initial steady state. This transformation applies also to consumption, capital, labor, price of capital, leverage, net worth, liquidity, real exchange rate, and the nominal depreciation rate (defined as $\Delta e_t = \frac{s_t}{s_{t-1}}\frac{\pi_t}{\pi_t^*}$). Some variables are plotted in deviations from the initial steady state, as a share of annualized GDP:

$$Cash/GDP = 100\frac{m_t - m_0}{4gdp_0},$$

and analogously for domestic deposits/GDP, central bank's loans/GDP, and trade balance (the latter is a flow variable and is not adjusted by $\frac{1}{4}$). Some variables are plotted in deviations from the initial steady state, as a share of annualized GDP expressed in terms of the foreign good:

$$CBDC/GDP = 100 s_0\frac{m_t^* - m_0^*}{4gdp_0},$$

and analogously for foreign deposits/GDP, and FXIs/GDP. Some variables are plotted in annualized level deviations:

$$CPI\ Inflation = 400\left(\pi_t - \pi_0\right),$$

and analogously for PPI inflation, for the real rate (defined as $\frac{r_t}{\mathbb{E}_t\pi_{t+1}}$), for the deposit rate (we plot the real one, $\frac{r_{Dt}}{\mathbb{E}_t\pi_{t+1}}$), and the credit spread ($r_{Bt+1} - \frac{r_{Dt}}{\pi_{t+1}}$). Finally, tax rates are expressed in levels (their steady state is 0).

3.1. Toward a stronger CBDC preference

We use the model to study the transition of the economy toward a new steady state with a higher foreign CBDC preference. We assume that the CBDC weight in the liquidity bundle gradually moves from 0 to 10% in 20 periods (5 years), simulating three scenarios: $\psi = 0$, thus the CBDC is deposit-like and the deposit weight falls from 20% to 10% (Fig. 1 and 2, blue solid line); $\psi = 1$, thus the CBDC is cash-like and the cash weight falls from 80% to 70% (Fig. 1 and 2, red dotted line); $\psi = 0.5$, and we assume that the CBDC is a liquidity-enhancing technology, so the weights of cash and deposit do not decrease (Fig. 1 and 2, black dashed line).[16] We solve the model using global methods, assuming perfect foresight.[17] This approach allows us to easily study the transition from one steady state to another one, without relying on linear or quadratic approximations. The drawback of this assumption is to neglect uncertainty issues related to the volatility of the exchange rate, which may be non-negligible given that the CBDC is denominated in foreign currency.

[16] We assume that the increase in the CBDC weight occurs at constant decreasing rates, to get a smooth dynamics.

[17] In all the simulations, we have verified that the bank's constraint remains binding along the transition.

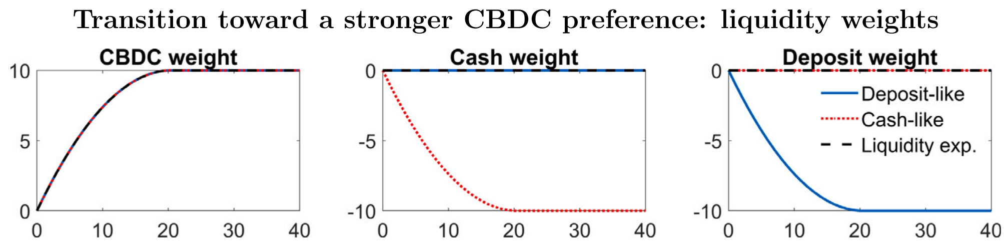

Fig. 1. In all simulations, the CBDC weight increases from 0 to 10% in 20 periods (5 years). In the deposit-like scenario (blue solid line), the deposit weight decreases from 20 to 10%. In the cash-like scenario (red dotted line), the cash weight decreases from 80 to 70%. In the liquidity-expansion shock (black dashed line), deposit and cash weights are unaltered. Variables are in deviation from the initial steady state. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

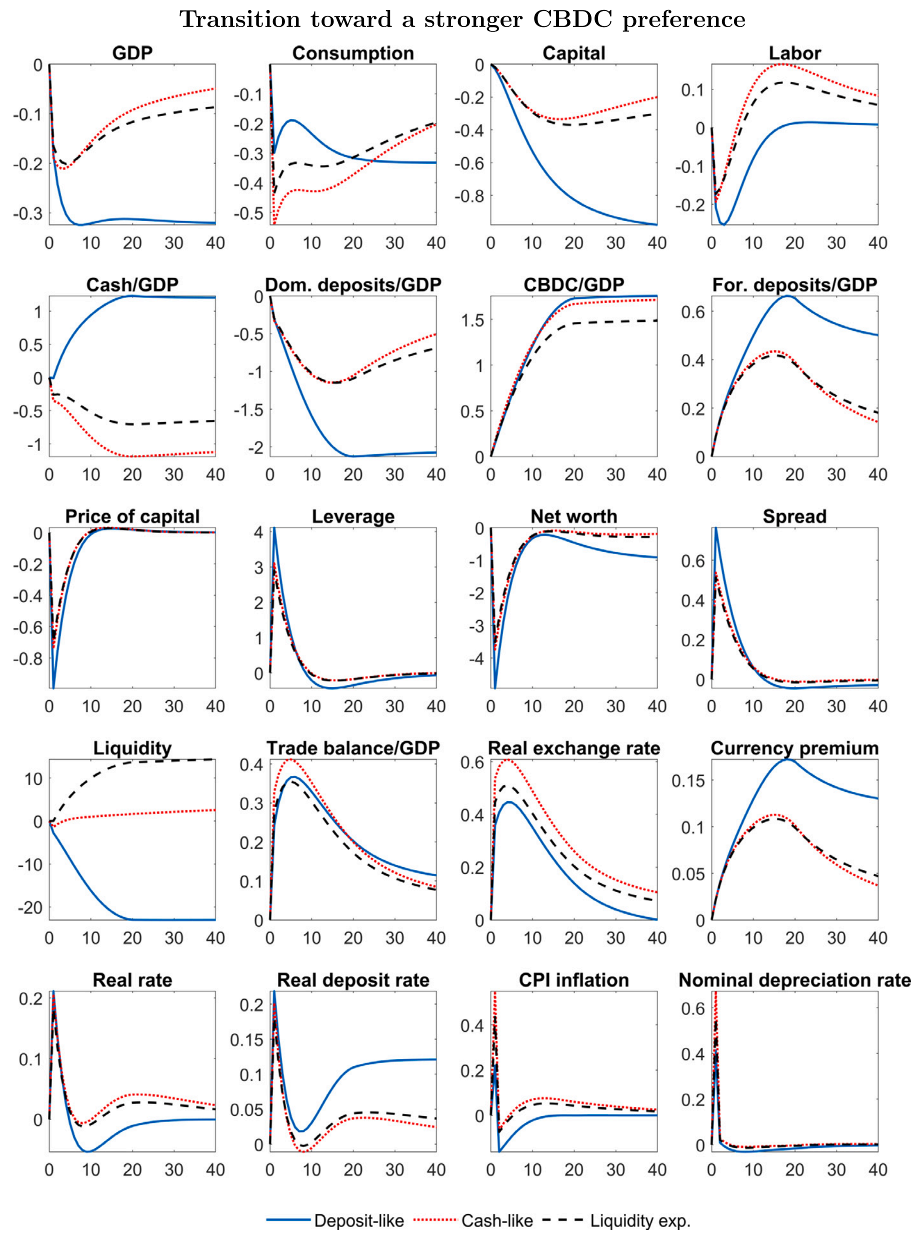

Fig. 2. Gradual increase in the CBDC weight $\tilde{\kappa}_M^* = 10\%$. In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: deposit-like CBDC ($\psi = 0$, $\tilde{\kappa}_D$ gradually decreases). Red dotted line: cash-like CBDC ($\psi = 1$, $\tilde{\kappa}_M$ gradually decreases). Black dashed line: liquidity-expansion shock ($\psi = 0.5$).

The three scenarios present several similarities. The increased preference for the CBDC depreciates the domestic currency, as households are raising the demand for a foreign asset, thus reducing the relative value of the domestic currency. The currency depreciation raises CPI inflation via the increase in the price of imports. The inflation rise triggers an interest-rate hiking by the central bank, which in turn increases the real rate and depresses consumption via the bond Euler equation. Domestic deposits fall in all scenarios, either directly as a result of the reduction of the deposit weight in households' liquidity bundle, or indirectly given the higher households' relative preference for the foreign CBDC and the higher attractiveness of bonds, which now are more remunerative. The reduction in households' deposit demand generates an increase in the deposit rate, both real (shown in the figure) and nominal. In a frictionless banking sector, a higher deposit rate would raise 1:1 the lending rate, depressing the demand for capital. In our frictional banking sector, this channel is amplified in the short term by two factors, which reduce the bank's net worth, triggering the financial accelerator: i) the reduction in the price of capital, as a result of a lower firms' capital demand, as the lending rate is higher; ii) the currency depreciation, which makes foreign deposits more costly for banks. The reduction in the net worth increases bank's leverage. Bankers have less skin in the game and their incentive to divert assets rises. In equilibrium, the cost of diverting assets has to go up: the credit spread increases in order to make the profitability of the bank higher. Firms face higher financing costs, reducing their capital demand. Banks substitute domestic with foreign deposits, driving a rise in the currency premium, which further depreciates the exchange rate. The trade balance improves, given the real depreciation, partially compensating the reduction in domestic absorption.[18] The long-term GDP loss is around $0.1 - 0.3\%$, given an increase in foreign CBDC holding close to 2% of annual GDP; the GDP loss is driven by the long-run increase in the deposit rate. Our results are in line with those of Burlon et al. (2022), which find that if domestic CBDC holding is 6.5% of annual GDP, the GDP loss is around 0.4% (Figure 3 in that paper). In our deposit-like scenario, the GDP fall is slightly larger than that in Burlon et al. (2022), probably due to the stronger financial frictions faced by a small emerging market compared to the euro area, the benchmark country in Burlon et al. (2022).

In the short/medium term there are three main differences between these scenarios. First, when the CBDC is cash-like, cash demand *falls* directly via the decrease in the cash weight κ_{Mt} (red dotted line). When the CBDC demand shock is liquidity-enhancing, cash *falls* via a substitution effect, given the relatively higher preference for the CBDC (black dashed line). When the CBDC is deposit-like, cash *increases* (blue solid line) for the following reason. The stock of domestic deposits is one order of magnitude larger than the stock of cash: the simultaneous reduction of the deposit weight κ_D and of deposit demand drives a very large reduction in the liquidity bundle (equation (26)), which increases the marginal utility of holding cash (equation (30)). Second, the increase in cash demand in the deposit-like scenario strongly mitigates the inflation rise (a positive money demand is typically deflationary, as money becomes scarcer), dampening the response of the central bank: the real policy rate increases by less over time, and the drop in consumption is smaller. Third, when the CBDC is deposit-like, the reduction in the deposit weight κ_{Dt} amplifies the increase in the deposit interest rate via the optimal deposit condition (equation (6)), reinforcing the spread rise and the reduction in capital demand: this channel leads to a greater fall in GDP and investment in the deposit-like scenario.[19]

The deposit-like scenario features a much stronger fall in domestic deposits also in the long run, as a result of the decrease of the deposit weight in the liquidity bundle, leading to a permanent increase in the deposit rate. Other things equal, the increase in the deposit rate implies a higher lending rate, which depresses consumption, investment, and GDP in the new steady state. This negative effect is exacerbated by the permanent rise in the currency premium, triggered by the permanent rise in foreign deposits, which replace domestic deposits in the bank's balance sheets.

We also highlight that the three scenarios differ only in parameter ψ, which can affect the dynamics in two ways. First, it affects the reaction of cash and deposits weights to a CBDC preference shock (equations (32) and (33)); second, it affects the disutility of assets. Shutting down the second channel, we would get almost identical responses: this implies that the security and anonymity terms play a minor role (otherwise households would not hold cash and CBDC, which yield lower rates and higher disutility compared to bonds).[20]

Do our results change if households could also invest in a foreign asset? Suppose foreign bonds are available for domestic households, even before the introduction of the foreign CBDC. As long as foreign bonds do not enter the liquidity bundle (consistently with Ferrari Minesso et al., 2022 and Burlon et al., 2022), our results would be identical because the foreign CBDC would still be perceived either similar to domestic cash or to domestic deposits. Conversely, if foreign bonds are included in the liquidity bundle and the foreign CBDC is perceived similar to foreign assets, the increase in the CBDC weight would imply an equal reduction in the foreign asset weight in the liquidity bundle, with minor economic implications. However, this last case is of limited interest, as the current debate is focusing on the risks of CBDCs that can compete with very liquid assets, such as cash and deposits.

3.1.1. Policy tools

Considering a deposit-like CBDC design ($\psi = 0$), which is the scenario characterized by the largest fall in economic activity, we examine the impact of a wide set of policy tools, that can be employed to dampen the effects of the transition: i) a sale of foreign reserves; ii) an easing of MPMs; iii) a tightening of CFMs on outflows; iv) a tightening of CFMs on inflows; v) targeting PPI inflation in the Taylor rule, as opposed to CPI inflation; vi) an exchange rate peg, that replaces the Taylor rule; vii) central bank's liquidity

[18] Under a producer currency pricing, this mitigation factor would be stronger.

[19] Another difference is the response of the liquidity bundle, which increases in the liquidity-expansion scenario. However, this does not lead to an increase in consumption, as liquidity and consumption enter separable in the utility function. If we assumed complementarity between consumption and liquidity, the increase in liquidity would have reduced the fall in consumption.

[20] These impulse response functions are available upon request.

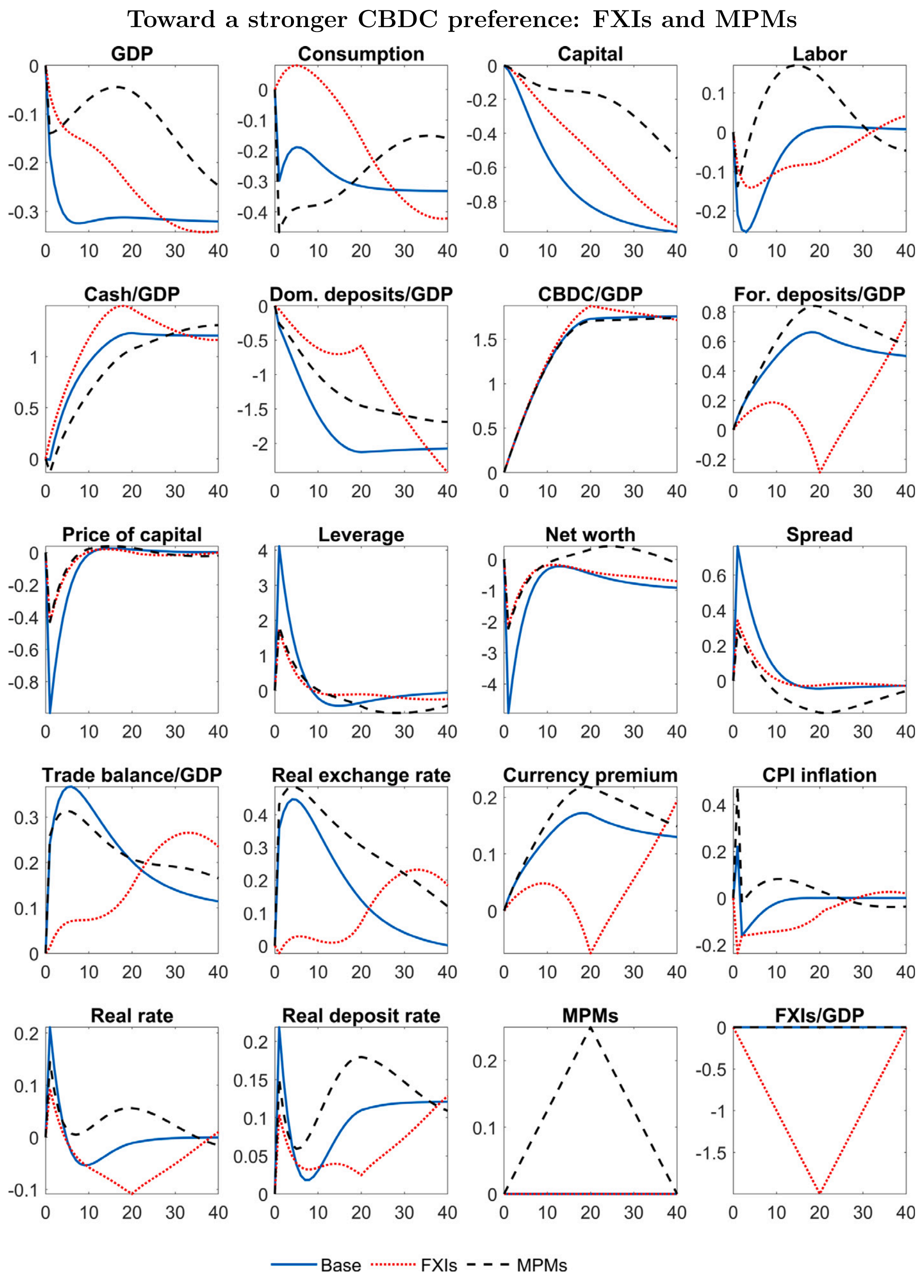

Fig. 3. Gradual increase in the CBDC weight $\tilde{\kappa}^*_M = 10\%$ in the deposit-like scenario ($\psi = 0$, $\tilde{\kappa}_D$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: no policy intervention. Red dotted line: FXIs. Black dashed line: MPMs.

injections in the banking sector. In the following figures, the blue solid line always refers to the baseline deposit-like scenario with no policy interventions. We keep assuming perfect foresight.

First, we plot a sterilized temporary sale in FX reserves, to counteract the depreciation of the domestic currency induced by the CBDC (Fig. 3, red dotted line). The FX sale is sterilized as it finances an increase in public bonds held by central bank. An FX sale is not neutral in our model, as it does not necessarily imply an equal purchase of foreign assets by the private sector.[21] We assume that the central bank keeps selling foreign bonds until period 20, when the CBDC preference shock reaches the peak and the sale of foreign bonds is 2% of GDP; from period 20 on foreign bonds held by the central bank gradually come back to the initial steady state.

[21] An FX sale is neutral if the following chain of events holds: i) the central bank sells foreign assets to foreign households, purchasing domestic bonds from domestic households; ii) domestic households exactly replace domestic bonds with domestic deposits; iii) banks exactly replace domestic deposits with foreign deposits. In our model, condition ii does not hold, as domestic deposits and bonds are imperfect substitutes; condition iii does not hold as the endogenous risk premium makes domestic and foreign deposits imperfect substitutes.

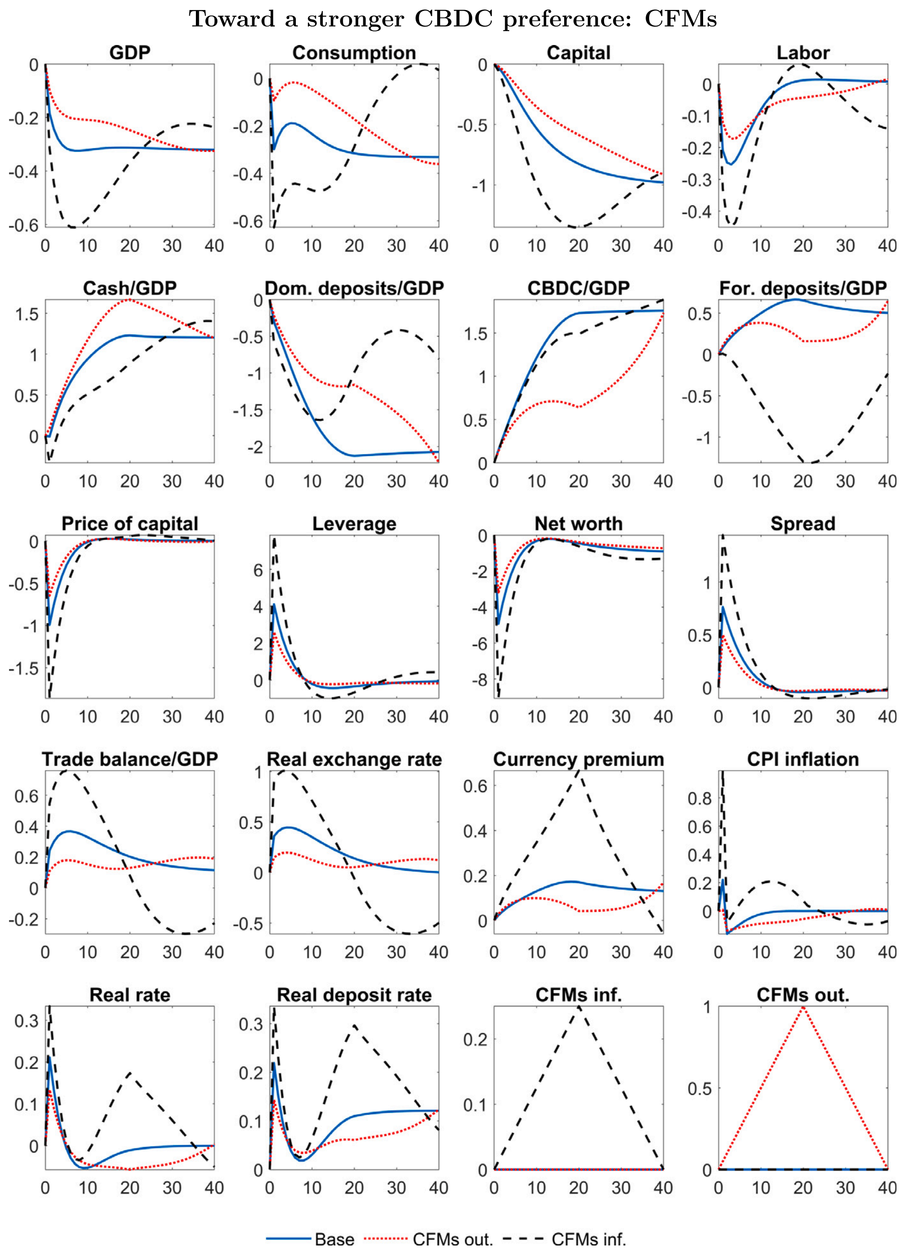

Fig. 4. Gradual increase in the CBDC weight $\tilde{\kappa}_M^* = 10\%$ in the deposit-like scenario ($\psi = 0$, $\tilde{\kappa}_D$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: no policy intervention. Red dotted line: CFM on outflows. Black dashed line: CFM on inflows.

This policy mitigates the real depreciation in the short term, alleviating the fall in the net worth and decreasing prices: the real rate, the deposit rate, and the spread rise by less, with positive spillovers to the real economy.

Second, we examine the effects of a MPM loosening, i.e. an increase in the macroprudential subsidy, which reaches 25 basis points in period 20 (Fig. 3, black dashed line), and then slowly decreases to 0. The policy directly addresses the financial friction, as it provides banks with more capital: the improvement in financial conditions allows banks to borrow a higher amount of deposits from both domestic and foreign investors compared to the baseline case, allowing them to lend more to domestic firms (capital decreases by less), limiting the output fall in the short term. Given the higher demand for foreign borrowing, the real exchange rate depreciates by more, leading to a higher increase in CPI inflation, which induces the central bank to increase the policy rate: the real policy rate increases by more in the medium term, exacerbating the short- and medium-term fall in consumption.

Third, we analyze a temporary increase in CFMs on outflows, modeled as a tax on the foreign CBDC (Fig. 4, red dotted line). Technological advances make it possible to embed CFMs in the design of CBDCs through the features of programmable money using the so called “smart contracts”, as pointed out recently by He et al. (2022). Again, the increase in the tax is gradual, to mirror the increase in the preference for the CBDC: the tax reaches 100 basis points in period 20, and then it starts decreasing. The tax

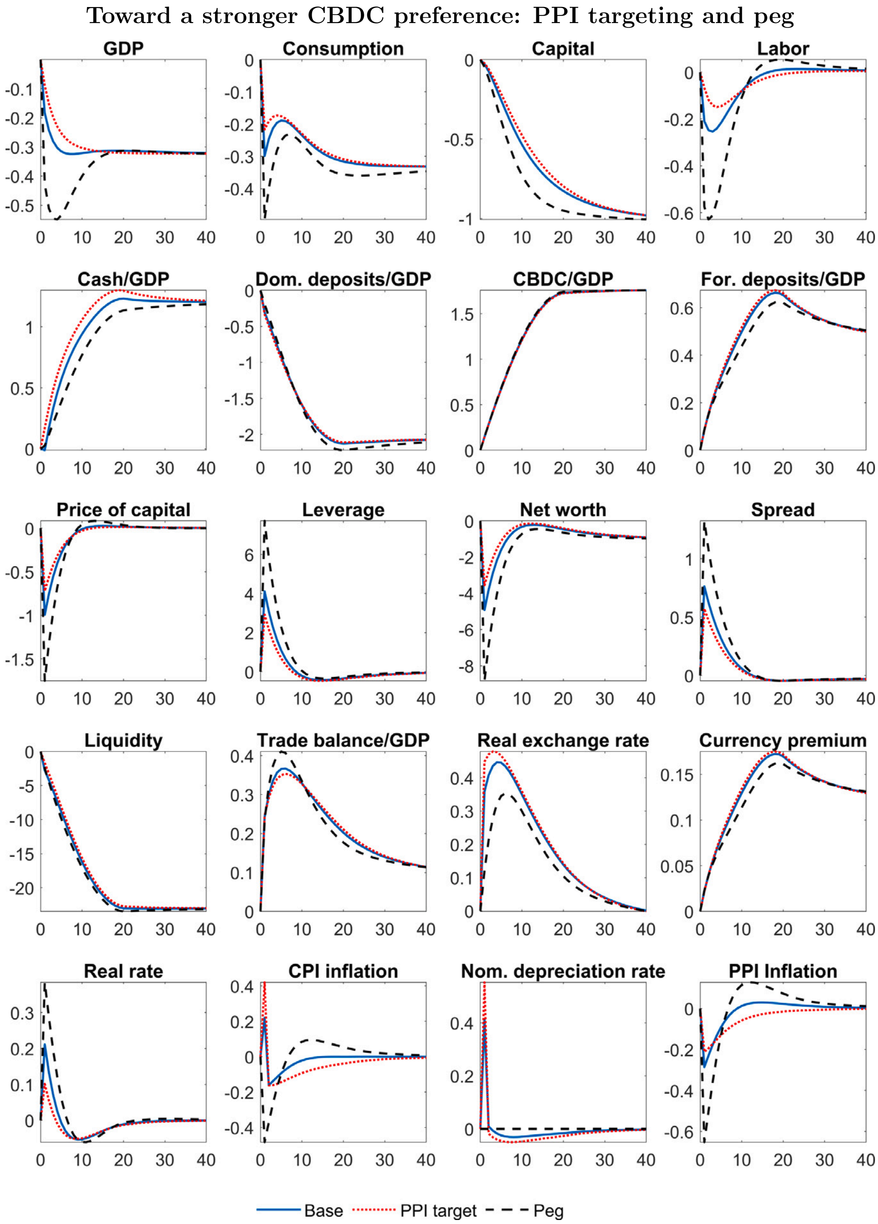

Fig. 5. Gradual increase in the CBDC weight $\tilde{\kappa}_M^* = 10\%$ in the deposit-like scenario ($\psi = 0$, $\tilde{\kappa}_D$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: baseline monetary policy. Red dotted line: PPI inflation targeting. Black dashed line: exchange rate peg.

temporarily limits the demand for CBDC, thus limiting the depreciation of the domestic currency. Households substitute CBDC with cash and deposits, mitigating the rise in the deposit rate. Banks borrow less from abroad, containing the rise in the currency premium. These effects dampen the fall in net worth and spread, with positive spillovers to the real economy.

Fourth, we study a temporary increase in CFMs on inflows, modeled as a tax on foreign deposits (Fig. 4, black dashed line). Compared to CFMs on outflows, we let the tax on inflows increase by less, to 25 basis points.[22] The tax increases the effective rate on foreign deposits, depreciating the domestic currency. Banks would like to borrow more from domestic households, who however have a lower preference for deposits: the deposit rate increases, magnifying the decline in production and triggering the financial accelerator.

Fifth, we consider a Taylor rule targeting PPI inflation π_{Ht}, rather than CPI inflation π_t (Fig. 5, red dotted line). PPI inflation is less affected by the preference shock than CPI inflation, which is directly impacted by the nominal depreciation. A central bank targeting PPI inflation raises the interest rate by less, with a positive impact on the economy.

[22] We do this as the elasticity of substitution between foreign and domestic deposits is higher than the elasticity of substitution between CBDC and domestic deposits: a 100 basis points increase in the tax on capital inflows would bear very strong consequences.

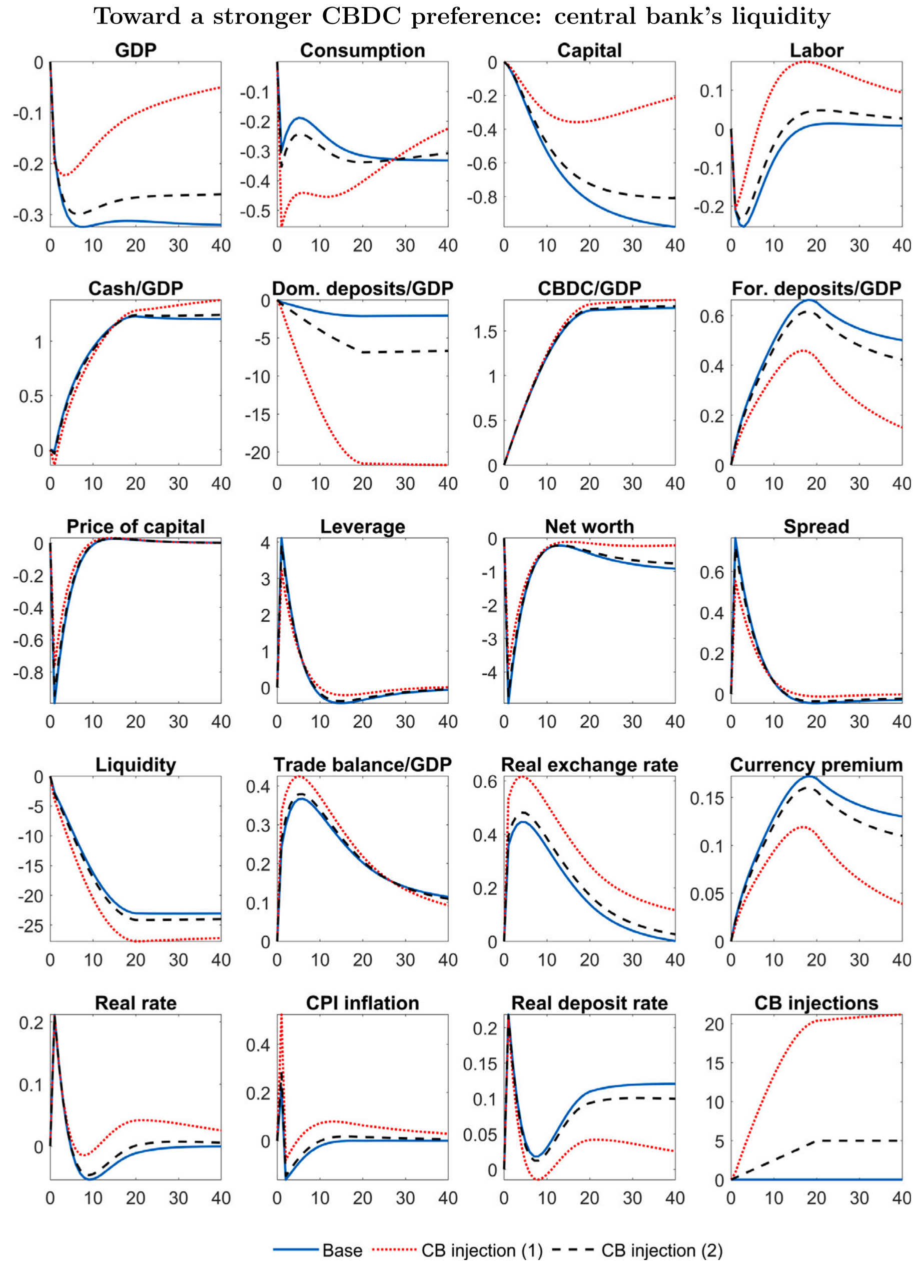

Fig. 6. Gradual increase in the CBDC weight $\tilde{\kappa}_M^* = 10\%$ in the deposit-like scenario ($\psi = 0$, $\tilde{\kappa}_D$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: no policy intervention. Red dotted line: the central bank sets r_{Ct} equal to the policy rate, while banks choose the optimal amount of central bank's loans. Black dashed line: liquidity injection by the central bank (r_{Ct} determined by the market).

Sixth, we replace the Taylor rule assuming that the country pegs the exchange rate (Fig. 5, black dashed line).[23] Avoiding a nominal depreciation after the CBDC preference shock means that the central bank needs to tighten the monetary stance, inducing an output drop. The deposit rate rises, for any given level of the spread the lending rate goes up, depressing capital and its price. In turn the net worth falls, the spread increases, and the fall in economic activity is exacerbated.

Seventh, we analyze the role of the central bank's liquidity facility (Fig. 6). In our model, domestic deposits and central bank's loans are perfect substitutes from the point of view of bankers, which implies that deposit rate r_{Dt} is equal to the central bank's loan rate r_{Ct}. We start assuming that the central bank sets r_{Ct}, while d_{Ct} is endogenously chosen by banks. In particular, we assume that the central bank's loan rate is equal to the policy rate:

[23] Given that in steady state domestic inflation is higher than foreign inflation, we are actually assuming that the central bank keeps a constant depreciation rate: the depreciation rate is always equal to its steady-state value, given by the ratio of inflation rates in the domestic and in the foreign economy.

$$r_{Ct} = r_t. \tag{34}$$

This policy is very effective in the long run, as it pins down the long-run deposit rate, that by arbitrage is equal to r_{Ct}, which in turn is equal to the policy rate set by the central bank: in the long-run, the deposit rate comes back to the initial steady state, eliminating the long-run reduction in economic activity (Fig. 6, red dotted line). However, this policy intervention has some drawbacks. First, the policy rate increases by more in the short term, to counteract the larger rise in inflation, arising for the larger exchange rate depreciation: this exacerbates the short-run fall in consumption.[24] Second, in the new steady-state central bank's loans to the banking sector are around 20% of GDP. Even if not modeled in our framework, these loans may cause losses for the public sector: to finance these loans, the central bank has to reduce its holding of public bonds, which implies that the government has to increase taxation or the stock of public debt held by the private sector. In our model higher lump-sum taxation or higher public debt are not costly for the economy as a whole: however, if only distortionary (rather than lump-sum) taxes are available or if a large stock of debt increases the probability of a sovereign default, central bank's loans (which require higher taxes or higher debt) may become costly. Having the banking sector strongly relying on central bank's funding in normal times would also distort market mechanisms by influencing the allocation of resources, as less productive banks would obtain funds in any case by the central bank.[25] Moreover, we have assumed that central bank's loans and deposits are perfect substitutes. However, central banks typically require collateral in order to lend to the banking sector: this would increase the cost for banks of using the central bank's facility.

We also explore what happens if the central bank sets d_{Ct}, leaving r_{Ct} to be determined by the market. We assume a more moderate 5% gradual increase in central bank's loans (Fig. 6, black dashed line): this policy is able to mitigate the fall in economic activity, but is less effective in comparison to the scenario in which the central bank controls the interest rate. If the gradual increase in central bank loans reaches 20% after 20 quarters, the outcome would be similar to the previous scenario.

These results on the effectiveness of different policy tools are confirmed in the cash-like scenario, at least from a qualitative point of view (figures are in the Appendix). In particular, FXIs, MPMs (red dotted line and black dashed line in Fig. C.1), CFMs on outflows (red dotted line in Fig. C.2), PPI targeting (red dotted line in Fig. C.3), and central bank's loans (black dashed line in Fig. C.4)[26] are able to mitigate the adverse effects of a gradual and permanent increase in the preference for a cash-like CBDC. Conversely, CFMs on inflows (black dashed line in Fig. C.2) and the exchange rate peg (black dashed line in Fig. C.3) amplify the short-term output fall.

3.2. An increase in the foreign interest rate

The introduction of a foreign CBDC is *per se* a shock, as we have learned from the previous analysis. A foreign CBDC may also change the dynamics of more standard shocks, such as movements in the foreign interest rate.

We solve the model using a first-order approximation around the steady state and we simulate the effect of a transitory 100-basis-point increase in the annualized foreign interest rate. The foreign rate follows an AR(1) process, with an autoregressive parameter equal to 0.95. All policy instruments and other foreign variables are in steady state. We consider four different scenarios. These scenarios differ in the steady state (within the same scenario, the initial and the final steady states are identical, as the shock is transitory). In the first scenario, we assume that households do not invest in the foreign CBDC, thus $\kappa_M^* = 0$ (Fig. 7, blue solid line). In the second scenario, we assume that the foreign CBDC weight κ_M^* in the liquidity function is 10%, as in the final steady state of the previous section (Fig. 7, red dotted line). In the third scenario we consider a very large CBDC steady-state holdings, 10% of GDP: we accomplish that by further increasing the CBDC weight ($\kappa_M^* = 0.189$) and assuming a steady-state CBDC rate of 50 basis points quarterly (Fig. 7, black dashed line).[27] Compared to the third scenario, in the fourth scenario we also assume that the foreign CBDC rate follows the same increase of the foreign interest rate (Fig. 7, green line with circle markers). In these scenarios, we always consider a deposit-like CBDC, though results are almost identical under a cash-like CBDC.[28]

In all scenarios, the increase in the foreign interest rate depreciates the domestic currency, thus raising CPI inflation.[29] The central bank responds by increasing the nominal policy rate, inducing a higher real policy rate and depressing consumption. The deposit rate rises as banks substitute foreign with domestic deposits, given the higher borrowing costs on the former. Banks face a reduction in the net worth for two reasons: the currency depreciation increases the value of foreign liabilities; the increase in the deposit rate pushes the lending rate up, reducing the demand of capital, and thus, its price. The four scenarios differ by how much the deposit rate increases: the more it rises, the more the credit spread goes up, and the harshest the output fall.

The scenario with no CBDC (blue solid line) and the scenario with an intermediate value of CBDC (red dotted line) yield quantitatively similar responses. In the scenario with an intermediate value of CBDC, households sell a fraction of their CBDC holdings, as

[24] The currency depreciates by more given equation (13), as the deposit rate increases by less.

[25] These reasons lead Gertler and Karadi (2011) to assume inefficiency costs for the central bank in conducting QE operations (i.e. directly lending to the corporate sector).

[26] This holds only if the interest rate on central bank's loans is determined by the market. Instead, if it is set by the central bank (red dotted line in Fig. C.4), the banking sector barely changes their borrowing from the central bank. This occurs as in the cash-like scenario the policy and the deposit rate do not diverge much: given $r_{Ct} = r_{Dt}$ by arbitrage, imposing $r_{Ct} = r_t$ implies $r_{Dt} = r_t$, which almost holds even without liquidity facility.

[27] To consider high CBDC steady state holdings, one should increase κ_M^*. However, we cannot set κ_M^* higher than 0.2, otherwise the deposit weight becomes negative. This is why we also change the steady-state CBDC rate.

[28] In this simulation, the CBDC preference shock is set to zero, hence the only difference between deposit-like and cash-like scenario is the disutility of assets, which does not play a prominent role.

[29] See Flaccadoro and Nispi Landi (2022) for an analysis of the response of inflation after a foreign interest rate shock.

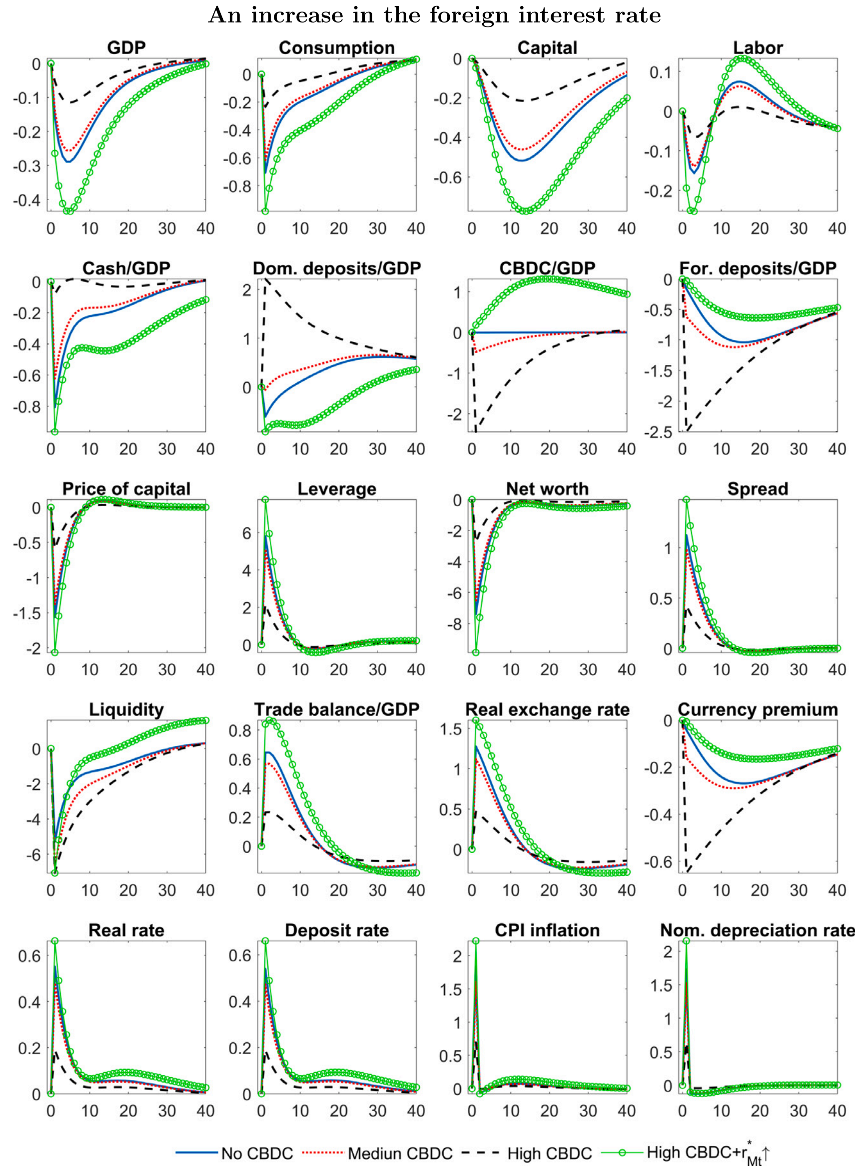

Fig. 7. The response of most variables is in % deviation from the steady state; inflation, interest rates, currency premium, and spread are reported in annualized level deviations; cash and domestic deposits are reported in deviations as a share of steady-state annualized GDP; CBDC and foreign deposits are reported in deviations as a share of steady-state annualized foreign-currency GDP. In period 0 the economy is in the steady state, in period 1 the shock hits (100 basis points increase in the annualized foreign rate). Blue solid line: no CBDC. Red dotted line: medium level of CBDC in the initial steady state. Black dashed line: high level of CBDC in the initial steady state. Green line with circle markers: high level of CBDC in the initial steady state and r^*_{Mt} increases as much as the foreign interest rate.

the foreign CBDC has become relatively less remunerative than domestic bonds, and increase their savings in domestic deposits. In equilibrium, this implies a slightly smaller rise in the deposit rate.

In the scenario with a high level of CBDC and a positive (yet constant) CBDC rate (black dashed line), the reduction in CBDC holdings is stronger: households massively replace CDBC with deposits, requiring a lower rise in the deposit rate to clear the market. In this case, a reduction in foreign CBDC holdings works similarly to a sale of FX reserves by the central bank: the country's foreign assets decrease, mitigating the currency depreciation that results from the foreign monetary tightening. In this scenario, the shock is almost offset, suggesting that a high stock of the foreign CBDC may serve as a prudential cushion against foreign shocks: this beneficial role of foreign CBDC may partially offset the negative implication for the long-run level of economic activity, explored in the previous section. However, this is the case only if the CBDC rate does not move, following the foreign interest rate shock. If the CBDC rate also rises, mimicking the behavior of the foreign interest rate, households do not have any incentive to reduce the stock of the foreign CBDC. They do the opposite and buy the foreign CBDC, attracted by a higher return (green line with circle markers). This is the worst scenario in terms of GDP loss, as it maximizes the reduction in deposit demand, and, as a result, the increase in the deposit rate, implying a stronger financial accelerator.

4. Sensitivity analysis

In this section we explore how results depend on some calibration choices. We increase the foreign CBDC final value, by increasing the final weight on the foreign CBDC κ^*_{Mt} and by introducing a CBDC return. We change the sensitivity of the currency premium to external debt (parameter κ_Z). We modify the initial steady state of cash, by changing the cash weight κ_M. We consider a scenario where the CBDC weight κ^*_M is already positive in the initial steady state, but the foreign CBDC is not available to households: in the first period, we assume that the CBDC becomes available, and we study the transition.

A transition to a new steady state with a larger CBDC weight in the liquidity bundle (19.5%, instead of 10%, as in the baseline model)[30] implies a more severe credit crunch and a greater reduction in GDP and consumption, in both the deposit-like (red dotted line in Fig. C.5) and the cash-like scenario (red dotted line in Fig. C.6), compared to the baseline specification (blue solid line in both figures). We further increase the final CBDC holding by introducing a CBDC remuneration of 50 basis points quarterly (Fig. C.5 and C.6, black dashed line, which refer to the deposit-like and cash-like scenario, respectively). The higher attractiveness of CBDC amplifies the negative consequences explored in the baseline analysis.

The IMF IPF and the BIS MFSF have stressed the fundamental role of countries' characteristics in shaping the absorption capacity to external shocks. The financial spillovers of a foreign CBDC are not an exception. The deepness of FX markets, captured in our model through parameter κ_Z, is one of these key features (the higher κ_Z, the more shallow FX markets). We replicate the analysis of the increased preference for the foreign CBDC, changing the value of κ_Z and focusing on the deposit-like case. When FX markets are relatively more shallow ($\kappa_Z = 0.05$, Fig. C.7, black dashed line), banks are less able to raise deposits from foreign investors in response to the increase in the domestic deposit rate. Larger financing costs for banks are transmitted to the productive sector through an increase in the lending rate, causing a more severe short-run drop in economic activity in comparison to the case in which FX markets are relatively deeper ($\kappa_Z = 0.005$, Fig. C.7, red dotted line). The baseline calibration described in the previous section ($\kappa_Z = 0.01$) is reported with a blue solid line.

The amount of cash holdings of the small open economy in the initial steady state affects the size of the output fall caused by the CBDC preference shock. In our baseline calibration we set the cash over GDP ratio to 7.4%, the mean value in our sample. We compare the baseline scenario (Fig. C.8, blue solid line) with two alternative scenarios characterized by a cash over GDP ratio equal to 5% (Fig. C.8, red dotted line) and to 10% (Fig. C.8, black dashed line); to do that, we change the cash weight κ_M from 0.8 to 0.660 and 0.895, respectively.[31] A larger value assigned to κ_M corresponds to a lower value for κ_D, the deposits weight in the liquidity bundle. The lower κ_D, the lower the marginal utility of deposits, which become less important to households: they strongly reduce deposits, when the steady state cash over GDP ratio is relatively higher (black dashed line). The opposite occurs when the ratio is lower (red dotted line). Again, when the reduction in domestic deposits is larger, the rise in the deposit rate is stronger, driving a sharper contraction in bank lending toward productive firms and a more severe reduction in economic activity.

Finally, we study a last experiment where we shock the supply, rather than the demand, of foreign CBDC. We assume that in period 0, the CBDC weight in the liquidity bundle is already $\kappa^*_M = 0.1$, but households are not allowed to invest in CBDC. From period 1 on households are allowed to buy the foreign CBDC, and the economy start adjusting toward the new steady state (Fig. C.9). The impulses responses are qualitatively similar to the liquidity-expansion scenario (Fig. 2, black dashed line): investment in the foreign CBDC goes immediately up, while cash and domestic deposits decrease; overall, the liquidity bundle is higher, given a large CBDC marginal utility, because before the shock $m^*_t = 0$ despite a positive CBDC weight. The currency depreciation boosts inflation, which drives an increase in the policy rate. Banks replace domestic with foreign deposits, causing a higher currency premium. The higher deposit rate drives an increase in the lending rate, which reduces capital demand and its price, depressing bank's net worth and boosting leverage and spread.[32]

5. Conclusions

Our results suggest that introducing a foreign CBDC in an emerging market economy may have a disruptive impact, especially if the CBDC is designed to be similar to domestic deposits. When households increase foreign CBDC holdings and reduce deposits, the deposit rate goes up, triggering an increase in the lending rate that depresses investments, inducing banks to rely more on foreign borrowing. The resulting contraction in the real activity is exacerbated in the short term by financial frictions in the banking sector.

We show that there are several policy instruments that can be deployed to smooth the negative impact of a foreign CBDC: easing MPMs, tightening CFMs on outflows, selling FX reserves, and a central bank's liquidity facility available to banks are appropriate policy measures when domestic residents start investing in the foreign CBDC. Moreover, while a central bank that targets PPI inflation is very effective in reducing the disruptive effects of the preference shock, a standard Taylor rule based on CPI inflation or an exchange rate peg are less suited.

We also report that a high stock of the foreign CBDC held by households may serve as a cushion to changes in the foreign interest rate, if the CBDC remuneration does not change accordingly.

Should the foreign CBDC be designed to be more similar to cash, the permanent reduction in economic activity would be more limited. However, our analysis is not considering that a gradual shift from domestic cash to the foreign CBDC as a means of payments

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[30] A value of 20% would eliminate deposits in the liquidity bundle in the deposit-like case, complicating the analysis.

[31] A ratio of 5% is approximately equal to that in Indonesia in 2019. A ratio of 10% is approximately equal to that in Poland (source: IFS).

[32] We carry out the experiment by assuming that the initial CBDC tax is such that households do not invest in CBDC: we set $\tau^O_t = 0.24$, which implies that $m^*_t = 0$. From period 1 on, we set $\tau^O_t = 0$.

can jeopardize monetary policy independence, especially in the extreme case in which domestic prices start to be denominated in foreign-currency units. Studying the interaction between financial stability and monetary independence issues for an emerging market investing in foreign CBDCs seems a promising avenue for future research.

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Appendix A. Model description

A.1. Households

There is a continuum of households of measure unity. In any period, a fraction $1-\upsilon$ of members of the households are workers, a fraction υ are bankers. Every banker stays banker in the next period with probability χ. It turns out that in every period $(1-\chi)\upsilon$ bankers become workers. It is assumed that $(1-\chi)\upsilon$ workers randomly become bankers, so the proportions of workers and bankers remain unchanged. Each banker manages a bank and transfers profits to her household. We further assume that each household's deposits are in banks that the household does not own. The different members of the household completely share idiosyncratic risks, and we can thus use the representative-household construct.

The representative household solves an intratemporal problem, to allocate consumption expenditure between domestic and foreign goods, and an intertemporal problem, to choose consumption, labor, and the asset allocation.

A.1.1. Intratemporal problem

The consumption bundle is defined as follows:

$$c_t = \left[(1-\gamma)^{\frac{1}{\eta}} c_{Ht}^{\frac{\eta-1}{\eta}} + \gamma^{\frac{1}{\eta}} c_{Ft}^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}},$$

where c_{Ht} and c_{Ft} denote consumption of domestic and foreign final good, respectively. For a given level of consumption, the optimal demand for the two goods reads:

$$c_{Ht} = (1-\gamma)\left(\frac{P_{Ht}}{P_t}\right)^{-\eta} c_t, \;\; c_{Ft} = \gamma\left(\frac{P_{Ft}}{P_t}\right)^{-\eta} c_t,$$

where P_{Ht} and P_{Ft} are the prices of domestic and imported goods, both expressed in domestic currency, and P_t is the domestic CPI:

$$P_t = \left[(1-\gamma) P_{Ht}^{1-\eta} + \gamma P_{Ft}^{1-\eta}\right]^{\frac{1}{1-\eta}}.$$

Given that the domestic economy is sufficiently small with respect to the foreign economy, the price of the foreign good P_{Ft} coincides with the foreign CPI, adjusted by the exchange rate: $P_{Ft} = e_t P_t^*$, where P_t^* is the foreign CPI (in foreign currency) and e_t is the nominal exchange rate (the price of one unit of foreign currency in terms of domestic currency). Define $p_{Ht} \equiv \frac{P_{Ht}}{P_t}$ and $p_{Ft} \equiv \frac{P_{Ft}}{P_t}$ as the price of domestic and foreign goods in terms of the domestic CPI. Notice that p_{Ft} can be interpreted as the real exchange rate s_t:

$$s_t = p_{Ft} = \frac{e_t P_t^*}{P_t},$$

and that we can re-write the CPI definition as follows:

$$1 = (1-\gamma)\left(p_{Ht}\right)^{1-\eta} + \gamma\left(s_t\right)^{1-\eta}. \tag{A.1}$$

The investment bundle is defined analogously and similar demand functions hold.

A.1.2. Intertemporal problem

The representative solves the following problem:

$$\max_{\{c_t,h_t,d_t,m_t,m_t^*,b_t,L_t,S_t,A_t\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\log c_t - \frac{h_t^{1+\varphi_H}}{1+\varphi_H} + \zeta_L \frac{L_t^{1-\varphi_L}}{1-\varphi_L} - \zeta_S \frac{S_t^{1+\varphi_S}}{1+\varphi_S} - \zeta_A \frac{A_t^{1+\varphi_A}}{1+\varphi_A} \right] \right\}$$

$$s.t.\begin{cases} c_t + b_t + d_t + m_t + s_t m_t^* = \frac{r_{t-1}}{\pi_t} b_{t-1} + \frac{r_{Dt-1}}{\pi_t} d_{t-1} + \\ + \frac{1}{\pi_t} m_t + \frac{r_{Mt-1}^*}{\pi_t^*} s_t \left(1 - \tau_{t-1}^O\right) m_{t-1}^* + w_t h_t + \Gamma_t - t_t \\ L_t = \left[\kappa_{Mt}^{\frac{1}{\varepsilon_L}} \left(m_t\right)^{\frac{\varepsilon_L - 1}{\varepsilon_L}} + \kappa_{Dt}^{\frac{1}{\varepsilon_L}} \left(d_t\right)^{\frac{\varepsilon_L - 1}{\varepsilon_L}} + \kappa_{Mt}^{*\frac{1}{\varepsilon_L}} \left(s_t m_t^*\right)^{\frac{\varepsilon_L - 1}{\varepsilon_L}} \right]^{\frac{\varepsilon_L}{\varepsilon_L - 1}} \\ S_t = m_t + \psi s_t m_t^* \\ A_t = d_t + (1 - \psi) s_t m_t^* \end{cases}$$

where h_t denotes hours of work in domestic firms; $d_t \equiv \frac{D_t}{P_t}$ and D_t denotes nominal deposits; $m_t \equiv \frac{M_t}{P_t}$ and M_t is cash; $m_t^* \equiv \frac{M_t^*}{P_t^*}$ and M_t^* is foreign CBDC, denominated in the foreign currency; L_t, S_t, and A_t are the liquidity bundle, the security and the anonymity function, respectively; r_t, r_{Dt}, r_{Mt}^* are the nominal gross interest rates on bonds, deposits, and the foreign CBDC, respectively, while the nominal gross return of cash is 1; $\pi_t \equiv \frac{P_t}{P_{t-1}}$ is the gross CPI inflation rate; w_t is the real hourly wage; Γ_t denotes profits from domestic firms, capital producers, and banks; t_t is a lump-sum tax; τ_t^O is a tax on foreign CBDC holdings. The optimality conditions yield the labor supply:

$$h_t^{\varphi_H} = \lambda_t w_t \tag{A.2}$$

and a Euler equation for each asset:

$$1 = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1} r_t}{\lambda_t \pi_{t+1}} \right) \tag{A.3}$$

$$1 = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t \pi_{t+1}} \right) + \frac{\zeta_L \left(\kappa_{Mt} \frac{L_t}{m_t} \right)^{\frac{1}{\varepsilon_L}} L_t^{-\varphi_L} - \zeta_S \left(m_t + \psi s_t m_t^* \right)^{\varphi_S}}{\lambda_t} \tag{A.4}$$

$$1 = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1} r_{Dt}}{\lambda_t \pi_{t+1}} \right) + \frac{\zeta_L \left(\kappa_{Dt} \frac{L_t}{d_t} \right)^{\frac{1}{\varepsilon_L}} L_t^{-\varphi_L} - \zeta_A \left[d_t + (1 - \psi) s_t m_t^* \right]^{\varphi_A}}{\lambda_t} \tag{A.5}$$

$$\begin{aligned} 1 = {} & \beta \mathbb{E}_t \left(\frac{\lambda_{t+1} s_{t+1} r_{Mt}^* \left(1 - \tau_t^O\right)}{\lambda_t \pi_{t+1}^* s_t} \right) + \\ & + \frac{\zeta_L \left(\kappa_{Mt}^* \frac{L_t}{s_t m_t^*} \right)^{\frac{1}{\varepsilon_L}} L_t^{-\varphi_L} - \zeta_S \psi \left(m_t + \psi s_t m_t^* \right)^{\varphi_S} - \zeta_A (1 - \psi) \left[d_t + (1 - \psi) s_t m_t^* \right]^{\varphi_A}}{\lambda_t}, \end{aligned} \tag{A.6}$$

where

$$\lambda_t = \frac{1}{c_t} \tag{A.7}$$

is the marginal utility of consumption.

A.2. Banks

There is a continuum of banks indexed by j. Each bank j features the following balance sheets:

$$f_t(j) = d_t(j) + d_{Ct}(j) + s_t d_t^*(j) + \left(1 + \tau_t^N\right) n_t(j),$$

where $f_t(j)$ denotes loans of bank j to domestic firms, in CPI terms; $d_t(j)$ represents domestic deposits; $d_t^*(j)$ denotes foreign deposits expressed in foreign currency; $d_{Ct}(j)$ denotes borrowing from a central bank's liquidity facility; $n_t(j)$ is bank j's net worth; τ_t^N is the macroprudential measure. Domestic firms borrow from banks to finance their capital expenditure $q_t k_t(j)$, where k_t denotes capital and q_t is its price. It holds: $f_t(j) = q_t k_t(j)$.

Conditional on surviving, the net worth of bank j is equal to profits, i.e. lending revenues minus borrowing costs:

$$n_{t+1}(j) = r_{Bt+1} q_t k_t(j) - \left[\frac{r_{Dt}}{\pi_{t+1}} d_t(j) + \frac{r_{Ct}}{\pi_{t+1}} d_{Ct}(j) + \frac{\Xi_t r_t^* \left(1 + \tau_t^I\right)}{\pi_{t+1}^*} s_{t+1} d_t^*(j) \right],$$

where r_{Bt} is the real lending rate; r_t^* is the foreign interest rate; r_{Ct} is the nominal rate on the liquidity facility; τ_t^I is a tax on foreign deposits; Ξ_t is an endogenous risk-premium:

$$\Xi_t = \bar{\Xi} \exp\left[\kappa_Z \left(d_t^* - \bar{d}^* \right) \right], \tag{A.8}$$

where d_t^* denotes aggregate foreign deposits.

Using the balance sheets condition to substitute for $d_t(j)$, we obtain a law of motion for $n_{t+1}(j)$:

$$n_{t+1}(j) = \left(r_{Bt+1} - \frac{r_{Dt}}{\pi_{t+1}}\right) q_t k_t(j) + \left(\frac{r_{Dt}}{\pi_{t+1}} - \frac{\Xi_t r_t^* \left(1+\tau_t^I\right)}{\pi_{t+1}^*} \frac{s_{t+1}}{s_t}\right) s_t d_t^*(j) +$$
$$+ \left(\frac{r_{Dt} - r_{Ct}}{\pi_{t+1}}\right) d_{Ct}(j) + \frac{r_{Dt}\left(1+\tau_t^N\right)}{\pi_{t+1}} n_t(j).$$

Depositors impose the following collateral constraint:

$$V_t(j) \geq \theta q_t k_t(j).$$

The value function of bank j reads:

$$V_t(j) = \max (1-\chi)\beta \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t} n_{t+1}(j)\right) + \chi \beta \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t} V_{t+1}(j)\right),$$

given that with probability $(1-\chi)$ banker j exits the market getting $n_{t+1}(j)$ at the beginning of period $t+1$, while with probability χ banker j continues the activity, getting the continuation value. The constraints of the value function are the evolution of the net worth and the incentive constraint.

Define with $\phi_t(j) \equiv \frac{q_t k_t(j)}{n_t(j)}$ the leverage of bank j. Gertler and Karadi (2011) show that the solution of the bank's problem gives an optimal leverage equal for each bank (so we can suppress the index j):

$$\phi_t = \frac{v_t}{\theta - \mu_t}, \tag{A.9}$$

where v_t is the marginal value of having one additional unit of net worth:

$$v_t = \beta \mathbb{E}_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \Omega_{t+1} \frac{r_{Dt}\left(1+\tau_t^N\right)}{\pi_{t+1}} \right\}; \tag{A.10}$$

μ_t is the marginal value in investing in loans

$$\mu_t = \beta \mathbb{E}_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \Omega_{t+1} \left(r_{Bt+1} - \frac{r_{Dt}}{\pi_{t+1}}\right) \right\}; \tag{A.11}$$

and Ω_t augments the household's stochastic discount factor $\beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t}$ to take into account that banks are not infinitely lived as households are, and that they value resources more than households, being subject to an incentive constraint:

$$\Omega_t = 1 - \chi + \chi \left(\mu_t \phi_t + v_t\right). \tag{A.12}$$

The solution of the bank's problem also gives an uncovered interest parity (UIP) condition between domestic and foreign deposits:

$$\beta \mathbb{E}_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \Omega_{t+1} \left(\frac{r_{Dt}}{\pi_{t+1}} - \frac{\Xi_t r_t^* \left(1+\tau_t^I\right)}{\pi_{t+1}^*} \frac{s_{t+1}}{s_t}\right) \right\} = 0, \tag{A.13}$$

and a parity condition between the interest rate on deposits and on the liquidity facility:

$$\beta \mathbb{E}_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \Omega_{t+1} \left(\frac{r_{Dt} - r_{Ct}}{\pi_{t+1}}\right) \right\} = 0 \tag{A.14}$$

A.3. Final-good firms

The domestic representative final-good firm uses the following CES aggregator to produce the domestic final good y_{Ht}:

$$y_{Ht} = \left[\int_0^1 y_{Ht}(i)^{\frac{\varepsilon_H - 1}{\varepsilon_H}} di \right]^{\frac{\varepsilon_H}{\varepsilon_H - 1}},$$

where $y_{Ht}(i)$ is an intermediate input produced by the intermediate firm i, whose price is $P_{Ht}(i)$. The optimal demand function for the intermediate input i reads:

$$y_{Ht}(i) = y_{Ht} \left(\frac{P_{Ht}(i)}{P_{Ht}}\right)^{-\varepsilon_H},$$

where P_{Ht} is the producer price index (PPI):

$$P_{Ht} = \left[\int_0^1 P_{Ht}(i)^{1-\varepsilon_H} \, di \right]^{\frac{1}{1-\varepsilon_H}}.$$

The foreign importer is a foreign final-good firm that uses the following CES aggregator to assemble the foreign imported good y_{Xt} (or the domestic exported good):

$$y_{Xt} = \left[\int_0^1 y_{Xt}(i)^{\frac{\varepsilon_X - 1}{\varepsilon_X}} \, di \right]^{\frac{\varepsilon_X}{\varepsilon_X - 1}},$$

where $y_{Xt}(i)$ denotes exports of the domestic firm i. The demand of the foreign final-good firm reads:

$$y_{Xt}(i) = y_{Xt} \left(\frac{P_{Xt}(i)}{P_{Xt}} \right)^{-\varepsilon_X}$$

where $P_{Xt}(i)$ is the price of the good sold by intermediate-good firm i to the rest of the world, denominated in foreign currency; P_{Xt} is the exports price index:

$$P_{Xt} = \left[\int_0^1 P_{Xt}(i)^{1-\varepsilon_X} \, di \right]^{\frac{1}{1-\varepsilon_X}}.$$

A.4. Intermediate-good firms

There is a continuum of firms indexed by i, producing a differentiated domestic input. The production function is the following:

$$y_{Ht}(i) + y_{Xt}(i) = \left(k_{t-1}(i)\right)^{\alpha} \left(h_t(i)\right)^{1-\alpha}.$$

Intermediate-good firms operate in monopolistic competition, so they set the price subject to the demand of final-good firms. They also set different prices in domestic markets ($P_{Ht}(i)$) and in foreign markets ($P_{Xt}(i)$). These firms pay quadratic adjustment costs $AC_{Ht}(i)$ and $AC_{Xt}(i)$, whenever they adjust prices with respect to a given benchmark:

$$AC_{Ht}(i) = \frac{\kappa_{PH}}{2} \left(\frac{P_{Ht}(i)}{P_{Ht-1}(i)} - \overline{\pi} \right)^2 P_{Ht} y_{Ht}$$
$$AC_{Xt}(i) = \frac{\kappa_{PX}}{2} \left(\frac{P_{Xt}(i)}{P_{Xt-1}(i)} - \pi^* \right)^2 P_{Xt} y_{Xt}.$$

Intermediate firms borrow from banks to buy physical capital from capital producers, which in turn buy non-depreciated capital from intermediate firms. Denoting with δ the capital depreciation rate and with

$$r_t^k = r_{Bt} q_{t-1} - (1-\delta) q_t \tag{A.15}$$

the rental rate of capital, the profit maximization problem of the generic firm i is the following:

$$\max \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[p_{Ht} y_{Ht}(i) + p_{Xt} y_{Xt}(i) - w_t h_t(i) - r_t^k k_{t-1}(i) - \frac{AC_{Ht}(i)}{P_t} - \frac{e_t AC_{Xt}(i)}{P_t} \right] \right\}$$
$$s.t. \begin{cases} y_{Ht}(i) = y_{Ht} \left(\frac{p_{Ht}(i)}{p_{Ht}} \right)^{-\varepsilon_H} \\ y_{Xt}(i) = y_{Xt} \left(\frac{p_{Xt}(i)}{p_{Xt}} \right)^{-\varepsilon_X} \\ y_{Ht}(i) + y_{Xt}(i) = \left(k_{t-1}(i)\right)^{\alpha} \left(h_t(i)\right)^{1-\alpha}, \end{cases}$$

where the maximization is taken over $\left\{ p_{Ht}(i), h_t(i), k_{t-1}(i) \, y_{Ht}(i), y_{Xt}(i), p_{Xt}(i) \right\}_{t=0}^{\infty}$, and $p_{Xt} \equiv \frac{e_t P_{Xt}}{P_t}$ is the price set in foreign markets, expressed in terms of the domestic CPI.

In equilibrium, firms choose the same price, same inputs, and same output, thus we can suppress the index i. The optimality conditions yield the input demands:

$$r_t^k = \alpha mc_t \frac{y_{Ht} + y_{Xt}}{k_{t-1}} \tag{A.16}$$
$$w_t = (1-\alpha) mc_t \frac{y_{Ht} + y_{Xt}}{h_t}, \tag{A.17}$$

and the optimal pricing, both in domestic and in foreign markets:

$$\pi_{Ht}\left(\pi_{Ht}-\overline{\pi}\right)=\beta\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{Ht+1}\left(\pi_{Ht+1}-\overline{\pi}\right)\frac{p_{Ht+1}y_{Ht+1}}{p_{Ht}y_{Ht}}\right]+\frac{\varepsilon_H}{\kappa_{PH}}\left(\frac{mc_t}{p_{Ht}}-\frac{\varepsilon_H-1}{\varepsilon_H}\right) \tag{A.18}$$

$$\pi_{Xt}\left(\pi_{Xt}-\pi^*\right)=\beta\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{Xt+1}\left(\pi_{Xt+1}-\pi^*\right)\frac{p_{Xt+1}y_{Xt+1}}{p_{Xt}y_{Xt}}\right]+\frac{\varepsilon_X}{\kappa_{PX}}\left(\frac{mc_t}{p_{Xt}}-\frac{\varepsilon_X-1}{\varepsilon_X}\right), \tag{A.19}$$

where mc_t is the real marginal cost; $\pi_{Ht}=\frac{P_{Ht}}{P_{Ht-1}}$ is PPI inflation, which can be written as:

$$\pi_{Ht}=\frac{p_{Ht}}{p_{Ht-1}}\pi_t; \tag{A.20}$$

$\pi_{Xt}=\frac{P_{Xt}}{P_{Xt-1}}$ is export price inflation, which can be written as:

$$\pi_{Xt}=\frac{p_{Xt}}{p_{Xt-1}}\frac{s_{t-1}}{s_t}\pi_t^*. \tag{A.21}$$

A.5. Capital producers

Domestic capital producers buy the investment good (i_t) from final-good firms and non-depreciated capital $(1-\delta)\,q_t k_{t-1}$ from intermediate firms in order to produce a capital good sold to intermediate firms ($q_t k_t$). Capital producers solve the following problem:

$$\max_{i_t,k_t}\mathbb{E}_0\left\{\sum_{t=0}^{\infty}\beta^t\frac{\lambda_t}{\lambda_0}\left[q_t k_t-(1-\delta)\,q_t k_{t-1}-i_t\right]\right\}$$

subject to the law of motion of capital:

$$k_t=(1-\delta)\,k_{t-1}+\left[1-\frac{\kappa_I}{2}\left(\frac{i_t}{i_{t-1}}-1\right)^2\right]i_t. \tag{A.22}$$

The first order condition yields the evolution of the price of capital:

$$1=q_t\left\{1-\frac{\kappa_I}{2}\left(\frac{i_t}{i_{t-1}}-1\right)^2-\kappa_I\frac{i_t}{i_{t-1}}\left(\frac{i_t}{i_{t-1}}-1\right)\right\}+$$
$$+\beta\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}q_{t+1}\left(\frac{i_{t+1}}{i_t}\right)^2\kappa_I\left(\frac{i_{t+1}}{i_t}-1\right)\right]. \tag{A.23}$$

A.6. Policy

The nominal interest rate is set according to the following Taylor rule:

$$\frac{r_t}{r}=\left(\frac{r_{t-1}}{r}\right)^{\rho_r}\left[\left(\frac{\pi_t}{\overline{\pi}}\right)^{\phi_\pi}\left(\frac{p_{Ht}y_{Ht}+p_{Xt}y_{Xt}}{p_{Ht-1}y_{Ht-1}+p_{Xt-1}y_{Xt-1}}\right)^{\phi_y}\right]^{1-\rho_r}, \tag{A.24}$$

where $p_{Ht}y_{Ht}+p_{Xt}y_{Xt}$ denotes gross domestic product gdp_t.

A.7. Foreign economy

Let F_t^* be the foreign demand for the domestic good. Given that the domestic demand for the foreign good is given by:

$$c_{Ft}+i_{Ft}=\gamma\left(\frac{P_{Ft}}{P_t}\right)^{-\eta}\left(c_t+i_t\right),$$

we postulate a symmetric expression for the foreign demand for the domestic bundle (assembled by the foreign importer):

$$F_t^*=\gamma^*\left(\frac{P_{Xt}}{P_t^*}\right)^{-\eta}\left(c_t^*+i_t^*\right),$$

which can be rewritten as follows:

$$F_t^*=\gamma^*\left(\frac{p_{Xt}}{s_t}\right)^{-\eta}y_t^*,$$

where $y_t^*=c_t^*+i_t^*$ is a measure of foreign demand. Given that the foreign economy is large compared to the domestic economy, we consider the following foreign variables as exogenous:

$$\left\{y_t^*,\pi_t^*,r_t^*,r_{Mt}^*\right\}.$$

A.8. Market clearing and equilibrium

Using the demand function for c_{Ht} and i_{Ht}, and foreign demand, we can get the market clearing condition for the domestic good sold in the domestic market,

$$y_{Ht} = (1-\gamma)\, p_{Ht}^{-\eta} \left(c_t + i_t\right) + g + \frac{\kappa_{PH}}{2} \left(\pi_{Ht} - \overline{\pi}\right)^2 y_{Ht}, \tag{A.25}$$

and in the foreign market:

$$y_{Xt} = \gamma^* \left(\frac{p_{Xt}}{s_t}\right)^{-\eta} y_t^* + \frac{\kappa_{PX}}{2} \left(\pi_{Xt} - \pi^*\right)^2 y_{Xt}, \tag{A.26}$$

Aggregating the balance sheets of banks we get:

$$q_t k_t = d_t + d_{Ct} + s_t d_t^* + \left(1 + \tau_t^N\right) n_t. \tag{A.27}$$

Given that all banks choose the same leverage, aggregating over banks we get:

$$\phi_t = \frac{q_t k_t}{n_t}. \tag{A.28}$$

Total net worth can be split between net worth of new bankers n_{yt} and net worth of old bankers n_{ot} $(n_t = n_{ot} + n_{yt})$. Given that only a fraction χ of bankers in period $t-1$ survive until period t and assuming that households transfer a share of assets $\frac{\iota}{1-\chi}$ from exiting bankers to new bankers (hence, $n_{yt} = \iota q_{t-1} k_{t-1}$), we can derive the following expression for the evolution of aggregate bank net worth:

$$\begin{aligned} n_t = \chi &\left[\left(r_{Bt} - \frac{r_{Dt-1}}{\pi_t}\right) q_{t-1} k_{t-1} + \left(\frac{r_{Dt-1}}{\pi_t} - \frac{\Xi_{t-1} r_{t-1}^* \left(1+\tau_{t-1}^I\right)}{\pi_t^*} \frac{s_t}{s_{t-1}}\right) s_{t-1} d_{t-1}^*\right] + \\ &+ \chi \left[\left(\frac{r_{Dt-1} - r_{Ct-1}}{\pi_t}\right) d_{Ct-1} + \frac{r_{Dt-1}\left(1+\tau_{t-1}^N\right)}{\pi_t} n_{t-1}\right] + \iota q_{t-1} k_{t-1}. \end{aligned} \tag{A.29}$$

Aggregating the production function of intermediate-good firms we get:

$$y_{Ht} + y_{Xt} = k_{t-1}^{\alpha} h_t^{1-\alpha}. \tag{A.30}$$

Using the budget constraint and the other equilibrium conditions, one can derive the aggregate resource constraint of the economy:

$$\begin{aligned} c_t + i_t + p_{Ht} g_t + \frac{\kappa_{PH}}{2} \left(\pi_{Ht} - \overline{\pi}\right)^2 p_{Ht} y_{Ht} + \frac{\kappa_{PX}}{2} \left(\pi_{Xt} - \pi^*\right)^2 p_{Xt} y_{Xt} + s_t \left(m_t^* + b_t^* - d_t^*\right) = \\ p_{Ht} y_{Ht} + p_{Xt} y_{Xt} + \frac{s_t}{\pi_t^*} \left(r_{Mt-1}^* m_{t-1}^* + r_{t-1}^* b_{t-1}^* - r_{t-1}^* \Xi_{t-1} d_{t-1}^*\right). \end{aligned} \tag{A.31}$$

The equilibrium of the model is described by equations (A.1)-(A.31), which form a system of 31 equations in 31 variables:

$$\begin{aligned} &\{\lambda_t, c_t, i_t, y_{Ht}, y_{Xt}, h_t, k_t, m_t, m_t^*, d_t, d_t^*, n_t, r_t, r_t^D, r_t^C, r_t^B, r_t^k, \Xi_t, w_t, q_t, mc_t, p_{Ht}, p_{Xt}, s_t, \ldots \\ &\pi_t, \pi_{Ht}, \pi_{Xt}, \mu_t, \nu_t, \Omega_t, \phi_t\}, \end{aligned}$$

given policy instruments:

$$\{g_t, \tau_t^N, \tau_t^O, \tau_t^I, b_t^*, d_{Ct}\},$$

foreign variables:

$$\{y_t^*, \pi_t^*, r_t^*, r_{Mt}^*\},$$

and asset demand shocks:

$$\{\kappa_{Dt}, \kappa_{Mt}, \kappa_{Mt}^*\}.$$

Appendix B. Steady state

B.1. Initial steady state

In this section we explain how to find the initial steady state of the model, i.e. the deterministic steady state where the transition starts. This is also the point around which we compute a first-order approximation when we simulate a transitory foreign interest rate shock. Variables without a time index are in the initial steady state. We adopt the following strategy. We calibrate ex ante ϕ, r_D, and the other following variables:

$$B^* = \frac{sb^*}{4gdp}$$
$$\mathcal{M} = \frac{m}{4gdp}$$
$$\mathcal{M}^* = \frac{sm^*}{4gdp}$$
$$rr = \frac{r}{\pi}$$
$$sp_D = r - r_D$$
$$\mathcal{D}^* = \frac{sd^*}{4gdp}$$
$$sp = r_B - \frac{r_D}{\pi}$$
$$G = \frac{p_H g}{gdp}$$

to compute ex post the following parameters[33]:

$$\left\{\theta, \zeta_A, b^*, \zeta_L, \kappa_M^*, \beta, \bar{\Xi}, \bar{d}^*, \iota, g, \right\}.$$

We compute the steady state as a function of $\left\{gdp, p_H, h\right\}$, in order to reduce the model in a system of three equations and three variables, easily solvable with a numerical optimizer. By equation (A.3), we find β:

$$\beta = \frac{1}{rr},$$

which implies by equation (A.24) and by the definition of the real interest rate:

$$\pi = \overline{\pi}$$
$$r = \frac{\overline{\pi}}{\beta}.$$

By equation (A.1), the real exchange rate reads:

$$s = \left[\frac{1 - (1-\gamma)\left(p_H\right)^{1-\eta}}{\gamma}\right]^{\frac{1}{1-\eta}}.$$

By equations (A.18)-(A.21), and by the definition of the nominal exchange rate it holds:

$$mc = \frac{\varepsilon_H - 1}{\varepsilon_H} p_H$$
$$\pi_H = \pi$$
$$p_X = p_H$$
$$\pi_X = \pi^*$$
$$\Delta e = \frac{\pi}{\pi^*}.$$

Using equation (A.26), we find y_X:

$$y_X = \gamma^* \left(\frac{p_{Xt}}{s_t}\right)^{-\eta} y^*.$$

Using the GDP definition, we find y_H:

$$y_H = \frac{gdp - p_X y_X}{p_H}.$$

Equation (A.23) implies:

$$q = 1.$$

Given the spread definitions, we find r_D and r_B:

[33] In most simulations, we set $\mathcal{M}^*$ to a very small value, meaning that κ_M^* is essentially 0.

$$r_D = r - sp_D$$
$$r_B = \frac{r_D}{\pi} + sp,$$

which imply by equation (A.15):

$$r^k = r_B - (1-\delta).$$

Equation (A.14) implies:

$$r_C = r_D.$$

Get the steady state of k by equation (A.16):

$$k = \alpha \frac{y_H + y_X}{r^k} mc,$$

and in turn we get i from equation (A.22):

$$i = \delta k.$$

Using equation (A.17) we can find w:

$$w = (1-\alpha)\frac{y_H + y_X}{h} mc.$$

Given $G, B^*, \mathcal{D}^*, \mathcal{M}$, and $\mathcal{M}^*$, we find g, b^*, d^*, m^*, and m^*, using their definitions:

$$g = \frac{G \cdot gdp}{p_H}$$
$$b^* = \frac{B^* 4gdp}{s}$$
$$d^* = \frac{\mathcal{D}^* 4gdp}{s}$$
$$m = \mathcal{M} 4gdp$$
$$m^* = \frac{\mathcal{M}^* 4gdp}{s}.$$

In the initial steady state we assume $d^* = \bar{d}^*$, which implies $\Xi = \bar{\Xi}$, by equation (A.8). We find $\bar{\Xi}$ using equation (A.13):

$$\bar{\Xi} = \frac{r_D/\pi}{r^*/\pi^*}.$$

Find consumption using equation (24):

$$c = p_H y_H + p_X y_X - p_H g - i - sm^*\left(1 - \frac{r_M^*}{\pi^*}\right) + sd^*\left(1 - \frac{\bar{\Xi} r^*}{\pi^*}\right) - sb^*\left(1 - \frac{r^*}{\pi^*}\right).$$

The marginal utility of consumption is given by equation (A.7):

$$\lambda = \frac{1}{c}.$$

We are left with three equations ((A.2), (A.25), and (A.30)):

$$w\lambda = h^{\varphi_H}$$
$$y_H = (1-\gamma)\left(p_H\right)^{-\eta}(c+i) + g$$
$$y_H + y_X = k^\alpha h^{1-\alpha},$$

where all variables depend on $\{gdp, h, p_H\}$. This system can be easily solved with a numerical optimizer. Now we need to find the variables and the missing parameters of the banking sector. Find n using equation (A.28).

$$n = \frac{k}{\phi}.$$

Use equation (A.29) to find ι:

$$\iota = \frac{1 - \chi\left(sp \cdot \phi + \frac{r_D}{\pi}\right)}{\phi}.$$

Use equations (A.10), (A.11), and (A.12) to get:

$$\Omega = \frac{1-\chi}{1-\chi\beta\left(sp\phi + \frac{r_D}{\pi}\right)}$$

$$v = \beta\Omega\frac{r_D}{\pi}$$

$$\mu = \beta\Omega sp.$$

Use equation (A.27) to find domestic deposits:

$$d = k - n - sd^* - d_C.$$

Use equation (A.9) to find θ:

$$\theta = \frac{v}{\phi} + \mu.$$

Finally, we find the parameters of the monetary utility functions. Using a numerical optimizer, we solve a system of three equations in three unknowns $\{\zeta_S, \zeta_L, \kappa_M^*\}$. The system includes equations (A.4), (A.5), and (A.6):

$$\frac{\zeta_L\left(\kappa_M\frac{L}{m}\right)^{\frac{1}{\varepsilon_L}} L^{-\varphi_L} - \zeta_S(m+\psi sm^*)^{\varphi_S}}{\lambda} = 1 - \beta\frac{1}{\pi}$$

$$\frac{\zeta_L\left(\kappa_D\frac{L}{d}\right)^{\frac{1}{\varepsilon_L}} L^{-\varphi_L} - \zeta_A[d+(1-\psi)sm^*]^{\varphi_A}}{\lambda} = 1 - \beta\frac{r_D}{\pi}$$

$$\frac{\zeta_L\left(\kappa_M^*\frac{L}{sm^*}\right)^{\frac{1}{\varepsilon_L}} L^{-\varphi_L} - \left\{\zeta_S\psi(m+\psi sm^*)^{\varphi_S} + \zeta_A(1-\psi)[d+(1-\psi)sm^*]^{\varphi_A}\right\}}{\lambda} = 1 - \beta\frac{r_M^*}{\pi^*},$$

given $\kappa_D = 1 - \kappa_M - \kappa_M^*$ and the definition of liquidity:

$$L = \left[\kappa_M^{\frac{1}{\varepsilon_L}} m^{\frac{\varepsilon_L-1}{\varepsilon_L}} + \kappa_D^{\frac{1}{\varepsilon_L}} d^{\frac{\varepsilon_L-1}{\varepsilon_L}} + \kappa_M^{*\frac{1}{\varepsilon_L}}\left(sm^*\right)^{\frac{\varepsilon_L-1}{\varepsilon_L}}\right]^{\frac{\varepsilon_L}{\varepsilon_L-1}}.$$

B.2. Final steady state

In the final steady state, the value for κ_M^* is higher. The procedure is similar to that for the initial steady state. The difference is that, of course, we use the same parameters of the initial steady state, thus we cannot set variables ex ante. The goal is to reduce the problem to a system of six equations in six variables $\{gdp, p_H, h, sp, m^*, d^*\}$. It is easy to see that for some variables the final steady state is equal to the initial one: this holds for $\{\pi, \pi_X, \pi_H, r, mc, \Delta e, q\}$. We find the other variables using the following steps. By equation (A.1), the real exchange rate reads:

$$s = \left[\frac{1-(1-\gamma)\left(p_H\right)^{1-\eta}}{\gamma}\right]^{\frac{1}{1-\eta}}.$$

Output for foreign markets:

$$y_X = \gamma^*\left(\frac{p_{Xt}}{s_t}\right)^{-\eta} y^*.$$

Given that $p_X = p_H$, using the GDP definition we find y_H:

$$y_H = \frac{gdp - p_X y_X}{p_H}.$$

In the final steady state, d^* is not necessarily equal to $\bar{d}^*$, which implies that Ξ is not necessarily equal to $\bar{\Xi}$. We find Ξ using equation (A.8):

$$\Xi = \bar{\Xi}\exp\left[\kappa_Z\left(d^* - \bar{d}^*\right)\right].$$

Find the deposit rate, using (A.13):

$$r_D = \frac{\Xi r^*}{\pi^*}\pi,$$

which gives $r_C = r_D$. Given the spread definition, we find r_B:

$$r_B = \frac{r_D}{\pi} + sp,$$

which implies by equation (A.15):

$$r^k = r_B - (1-\delta).$$

Once we have r^k, we can get the steady state of k by (A.16):

$$k = \alpha \frac{y_H + y_X}{r^k} mc,$$

and in turn we get i from equation (A.22):

$$i = \delta k.$$

Using equation (A.17) we can find w:

$$w = (1-\alpha)\frac{y_H + y_X}{h} mc.$$

Find consumption using equation (24):

$$c = p_H y_H + p_X y_X - p_H g - i - sm^* \left(1 - \frac{r_M^*}{\pi^*}\right) + sd^* \left(1 - \frac{\Xi r^*}{\pi^*}\right) - sb^* \left(1 - \frac{r^*}{\pi^*}\right).$$

The marginal utility of consumption is given by equation (A.7):

$$\lambda = \frac{1}{c}.$$

Use equation (A.29) to find n:

$$n = \frac{(\chi sp + \iota)\cdot k}{1 - \chi \frac{r_D}{\pi}}$$

Use equation (A.28) to find ϕ:

$$\phi = \frac{k}{n}.$$

Use equations (A.10), (A.11), and (A.12) to get:

$$\Omega = \frac{1-\chi}{1 - \chi\beta\left(sp\phi + \frac{r_D}{\pi}\right)}$$

$$\nu = \beta\Omega \frac{r_D}{\pi}$$

$$\mu = \beta\Omega sp.$$

Use equation (A.27) to find domestic deposits:

$$d = k - n - sd^* - d_C.$$

Use equation (A.5) to find L:

$$L = \left\{ \frac{\zeta_A \left[d + (1-\psi) sm^*\right]^{\varphi_A} + \lambda - \lambda\beta\left(\frac{r_D}{\pi}\right)}{\zeta_L \left(\frac{\kappa_D}{d}\right)^{\frac{1}{\varepsilon_L}}} \right\}^{\frac{\varepsilon_L}{1-\varepsilon_L \varphi_L}}.$$

Use the definition of the liquidity bundle to find m:

$$m = \left[\kappa_M^{-\frac{1}{\varepsilon_L}} \left(L^{\frac{\varepsilon_L - 1}{\varepsilon_L}} - \kappa_D^{\frac{1}{\varepsilon_L}} d^{\frac{\varepsilon_L - 1}{\varepsilon_L}} - \kappa_M^{*\frac{1}{\varepsilon_L}} \left(sm^*\right)^{\frac{\varepsilon_L - 1}{\varepsilon_L}}\right)\right]^{\frac{\varepsilon_L}{\varepsilon_L - 1}}.$$

We are left with six equations ((A.2), (A.4), (A.6), (A.9) (A.25), and (A.30)):

$$w = \frac{h^{\varphi_H}}{\lambda}$$

$$1 = \beta\left(\frac{1}{\pi}\right) + \frac{\zeta_L \left(\kappa_M \frac{L}{m}\right)^{\frac{1}{\varepsilon_L}} l^{-\varphi_L} - \zeta_S \left(m + \psi sm^*\right)^{\varphi_S}}{\lambda}$$

$$1 = \beta\left(\frac{r_M^*}{\pi^*}\right) - \frac{\zeta_S \psi \left(m + \psi sm^*\right)^{\varphi_S} + \zeta_A (1-\psi)\left[d + (1-\psi) sm^*\right]^{\varphi_A} - \zeta_L \left(\kappa_M^* \frac{L}{sm^*}\right)^{\frac{1}{\varepsilon_L}} L^{-\varphi_L}}{\lambda}$$

$$\phi = \frac{\nu}{\theta - \mu}$$
$$y_H = (1-\gamma)\left(p_H\right)^{-\eta}(c+i)+g$$
$$y_H + y_X = k^{\alpha} h^{1-\alpha},$$

where all variables depend on $\left\{gdp, p_H, h, sp, m^*, d^*\right\}$.

Appendix C. Additional figures

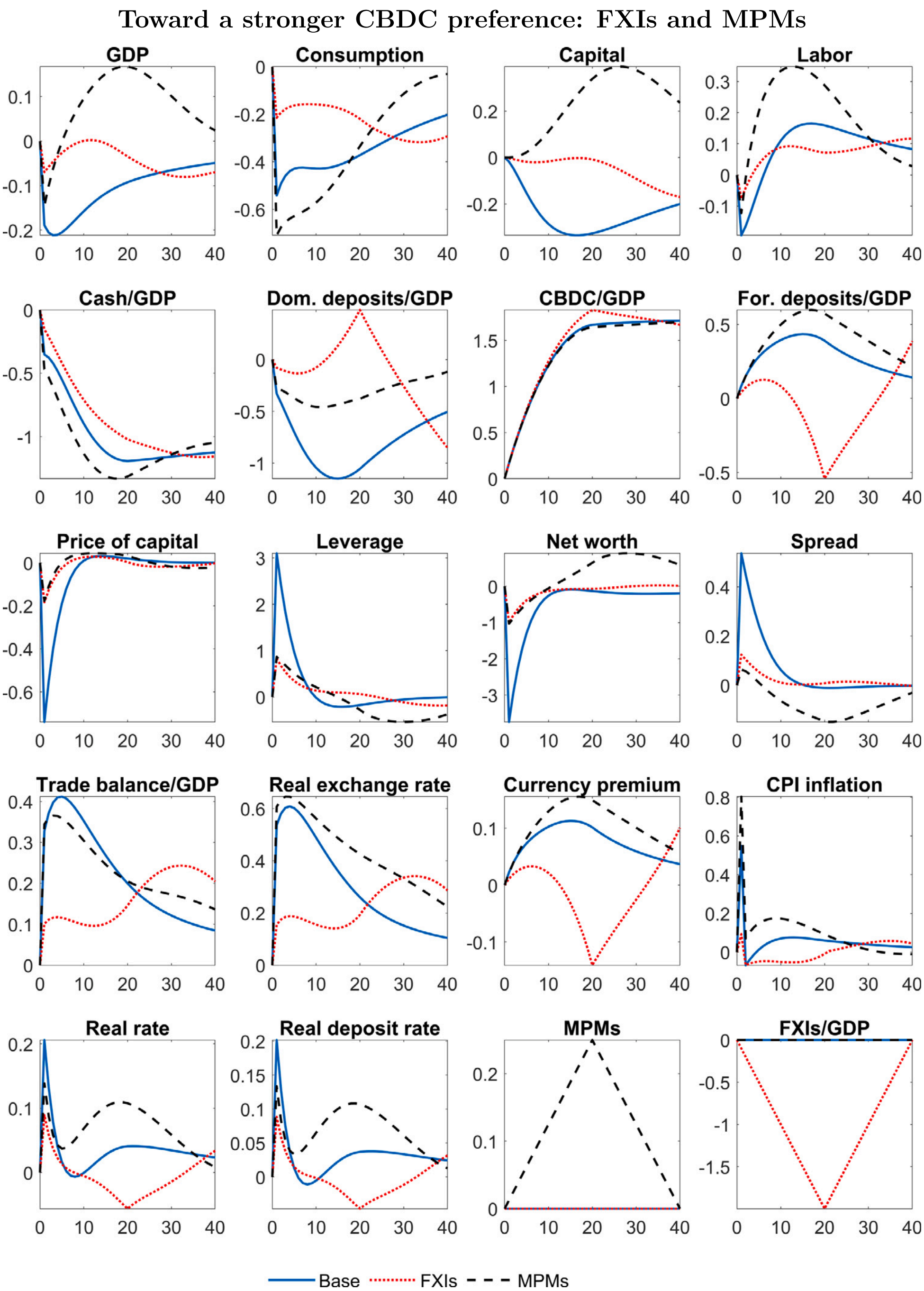

Fig. C.1. Gradual increase in the CBDC weight $\tilde{\kappa}^*_M = 10\%$ in the cash-like scenario ($\psi = 1$, $\tilde{\kappa}_M$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: no policy intervention. Red dotted line: FXIs. Black dashed line: MPMs.

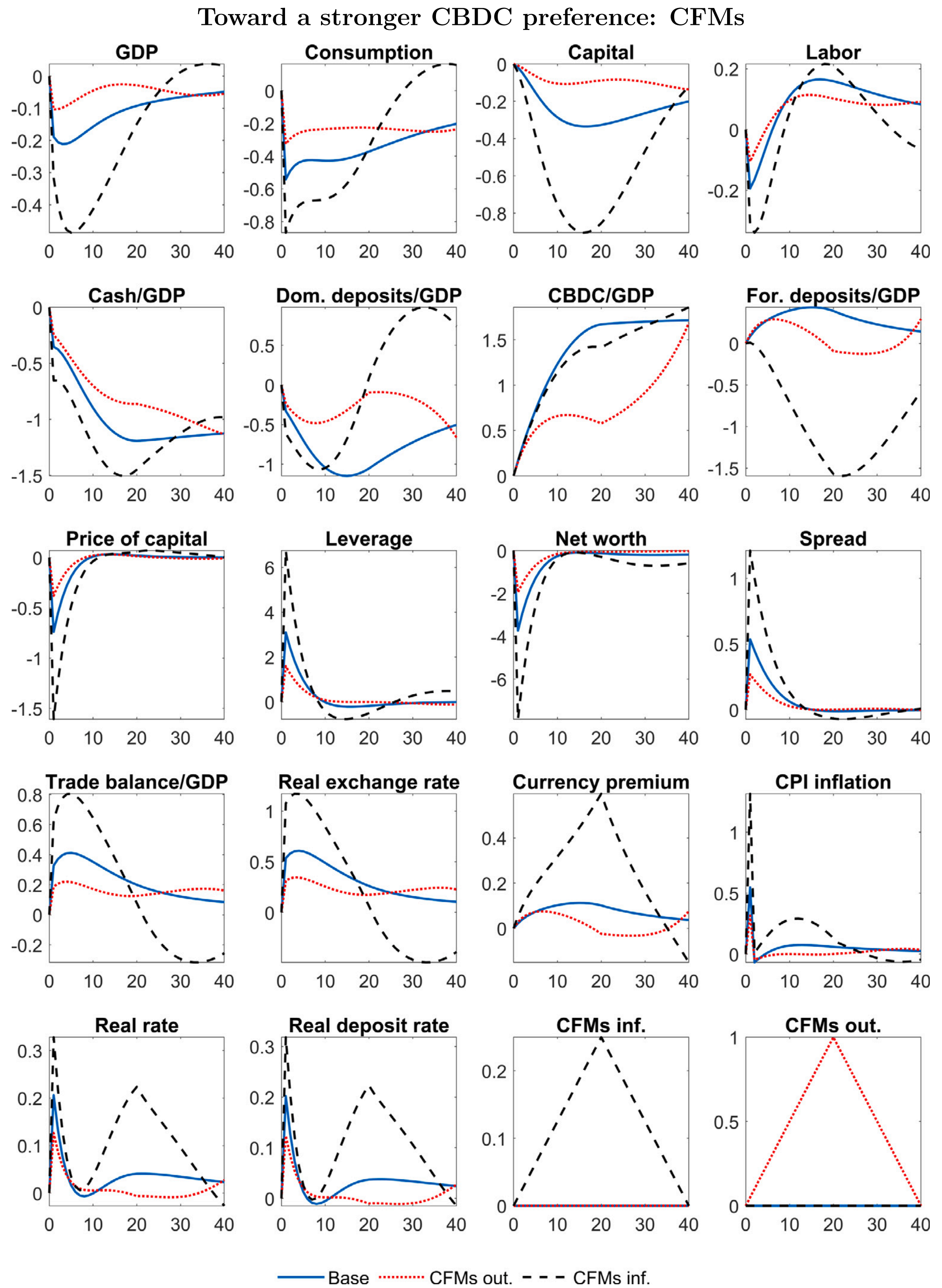

Fig. C.2. Gradual increase in the CBDC weight $\tilde{\kappa}_M^* = 10\%$ in the cash-like scenario ($\psi = 1$, $\tilde{\kappa}_M$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: no policy intervention. Red dotted line: CFM on outflows. Black dashed line: CFM on inflows.

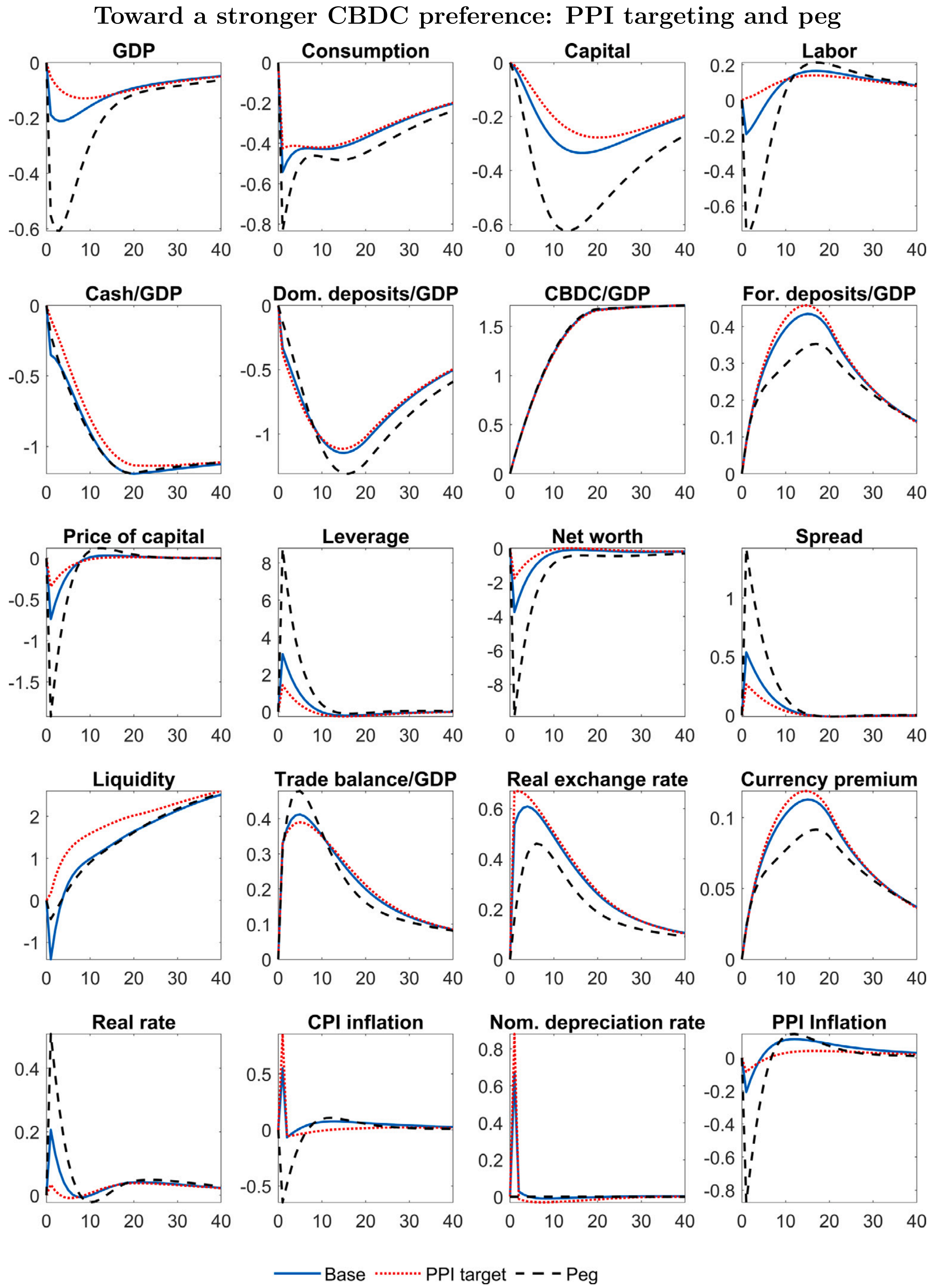

Fig. C.3. Gradual increase in the CBDC weight $\tilde{\kappa}_M^* = 10\%$ in the cash-like scenario ($\psi = 1$, $\tilde{\kappa}_M$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: baseline monetary policy. Red dotted line: PPI inflation targeting. Black dashed line: exchange rate peg.

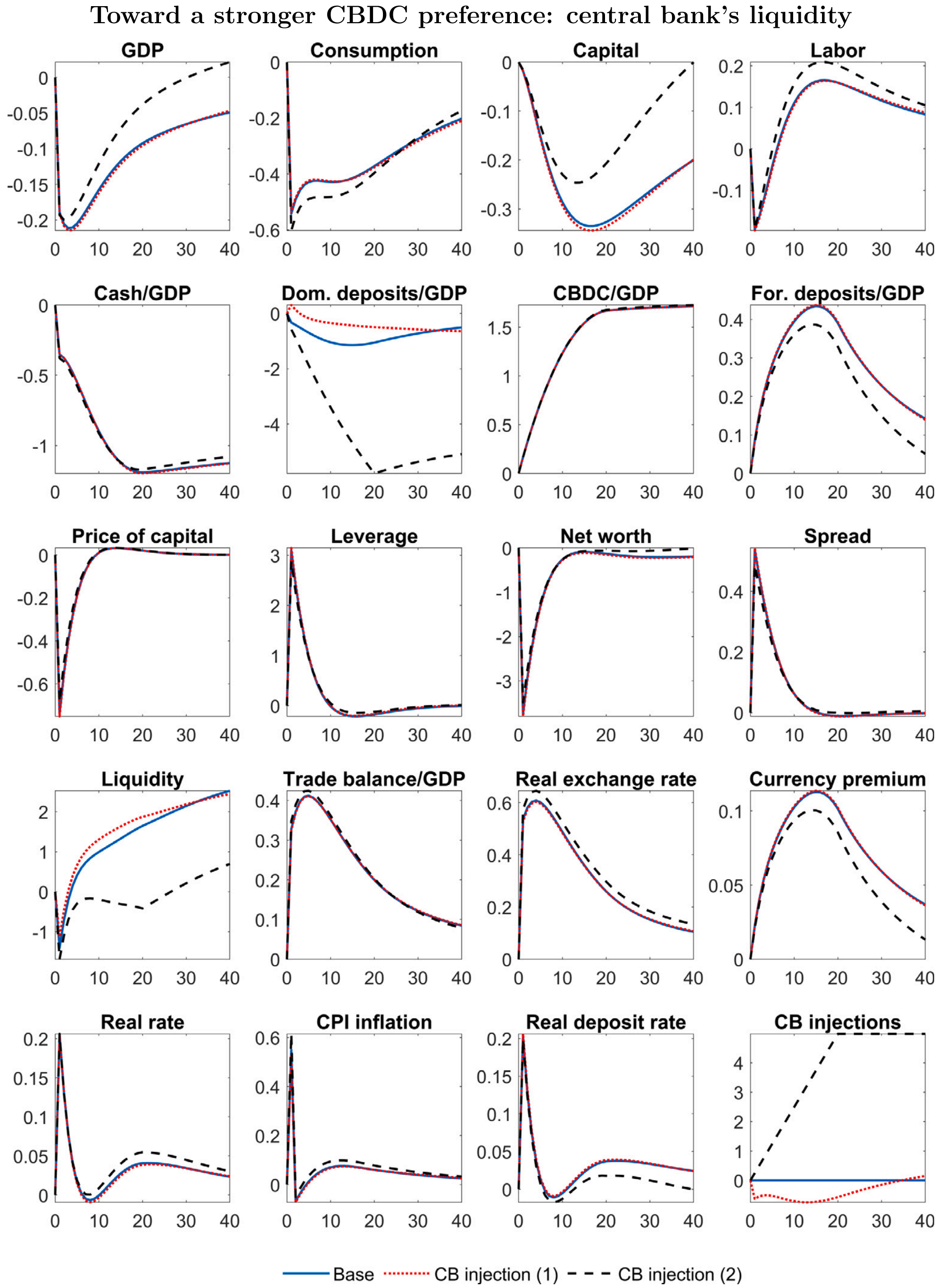

Fig. C.4. Gradual increase in the CBDC weight $\tilde{\kappa}_M^* = 10\%$ in the cash-like scenario ($\psi = 1$, $\tilde{\kappa}_M$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: no policy intervention. Red dotted line: the central bank sets r_{C_t} equal to the policy rate, while banks choose the optimal amount of central bank's loans. Black dashed line: liquidity injection by the central bank (r_{C_t} determined by the market).

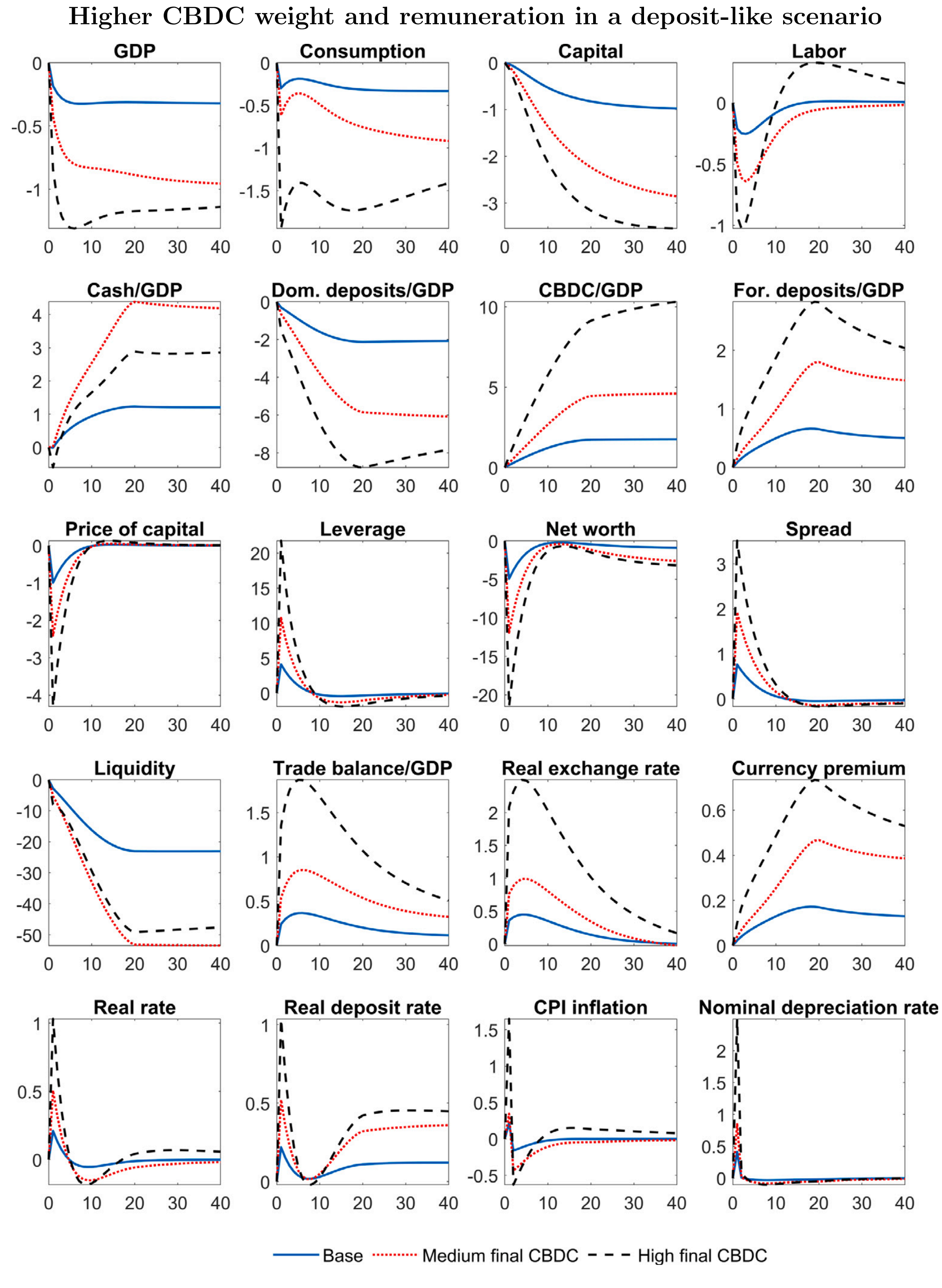

Fig. C.5. Greater increase in the CBDC weight and higher CBDC remuneration in a deposit-like scenario ($\psi = 0$, $\tilde{\kappa}_D$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: baseline increase in the CBDC weight ($\tilde{\kappa}^*_M = 10\%$) and zero-interest CBDC. Red dotted line: greater increase in the CBDC weight ($\tilde{\kappa}^*_M = 19.5\%$) and zero-interest CBDC. Black dashed line: greater increase in the CBDC weight ($\tilde{\kappa}^*_M = 19.5\%$) and higher CBDC remuneration $r^*_M = 1.005$.

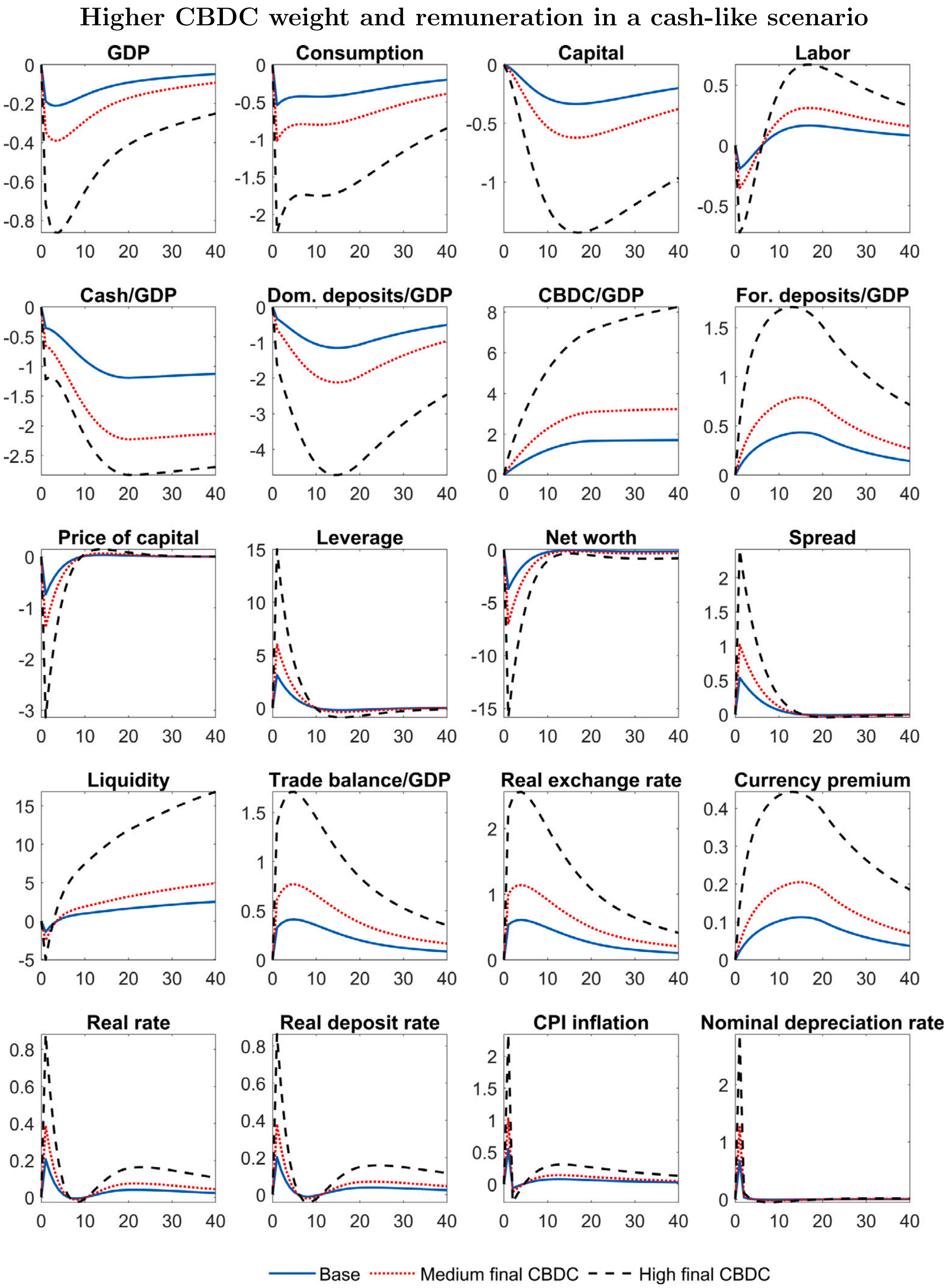

Fig. C.6. Greater increase in the CBDC weight and higher CBDC remuneration in a cash-like scenario ($\psi = 1$, $\tilde{\kappa}_M$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: baseline increase in the CBDC weight ($\tilde{\kappa}^*_M = 10\%$) and zero-interest CBDC. Red dotted line: greater increase in the CBDC weight ($\tilde{\kappa}^*_M = 19.5\%$) and zero-interest CBDC. Black dashed line: greater increase in the CBDC weight ($\tilde{\kappa}^*_M = 19.5\%$) and higher CBDC remuneration $r^*_M = 1.005$.

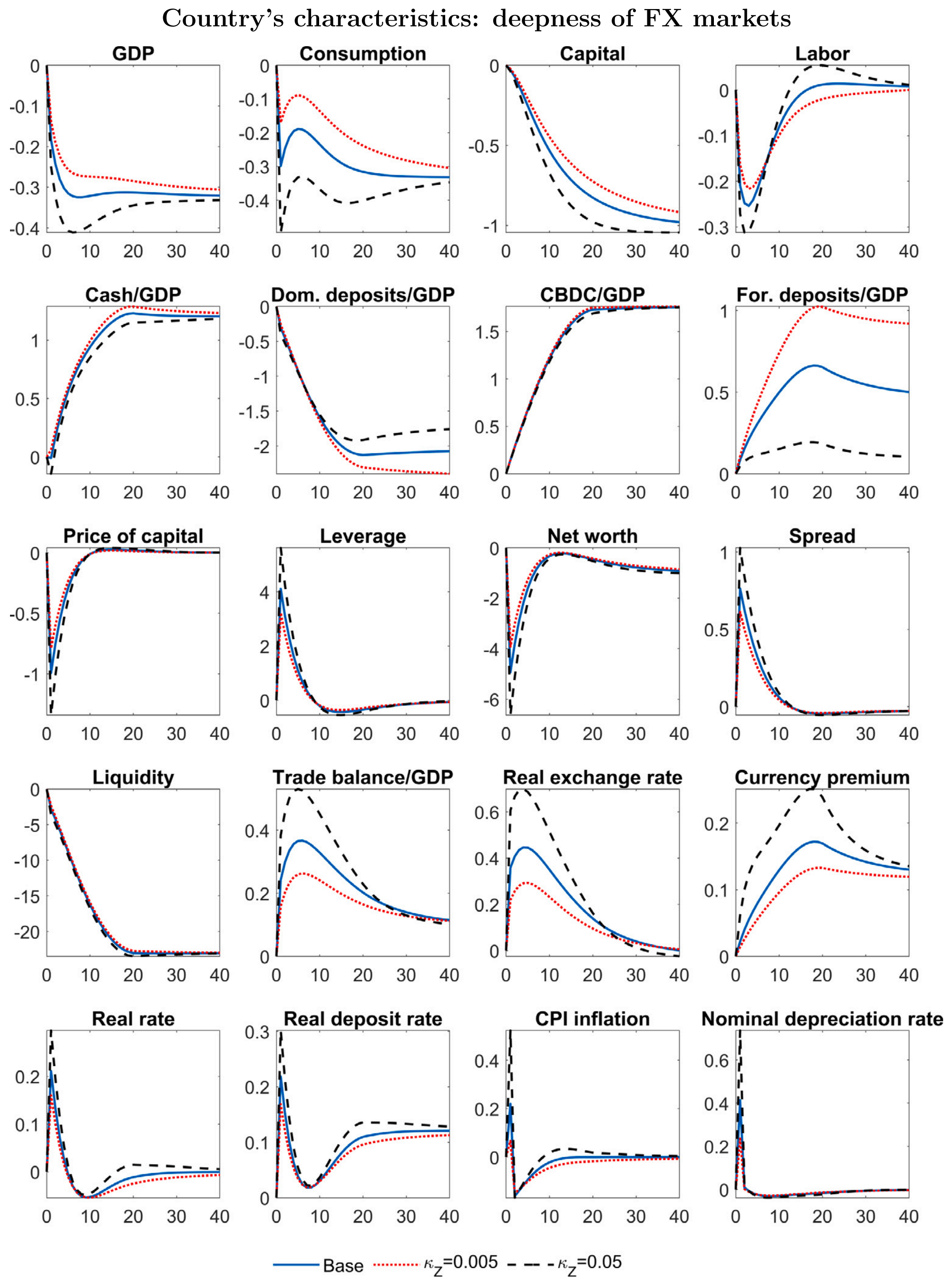

Fig. C.7. Gradual increase in the CBDC weight $\tilde{\kappa}^*_M = 10\%$ in the deposit-like scenario ($\psi = 0$, $\tilde{\kappa}_D$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: baseline scenario ($\kappa_Z = 0.01$). Red dotted line: deep FX markets ($\kappa_Z = 0.005$). Black dashed line: shallow FX markets ($\kappa_Z = 0.05$).

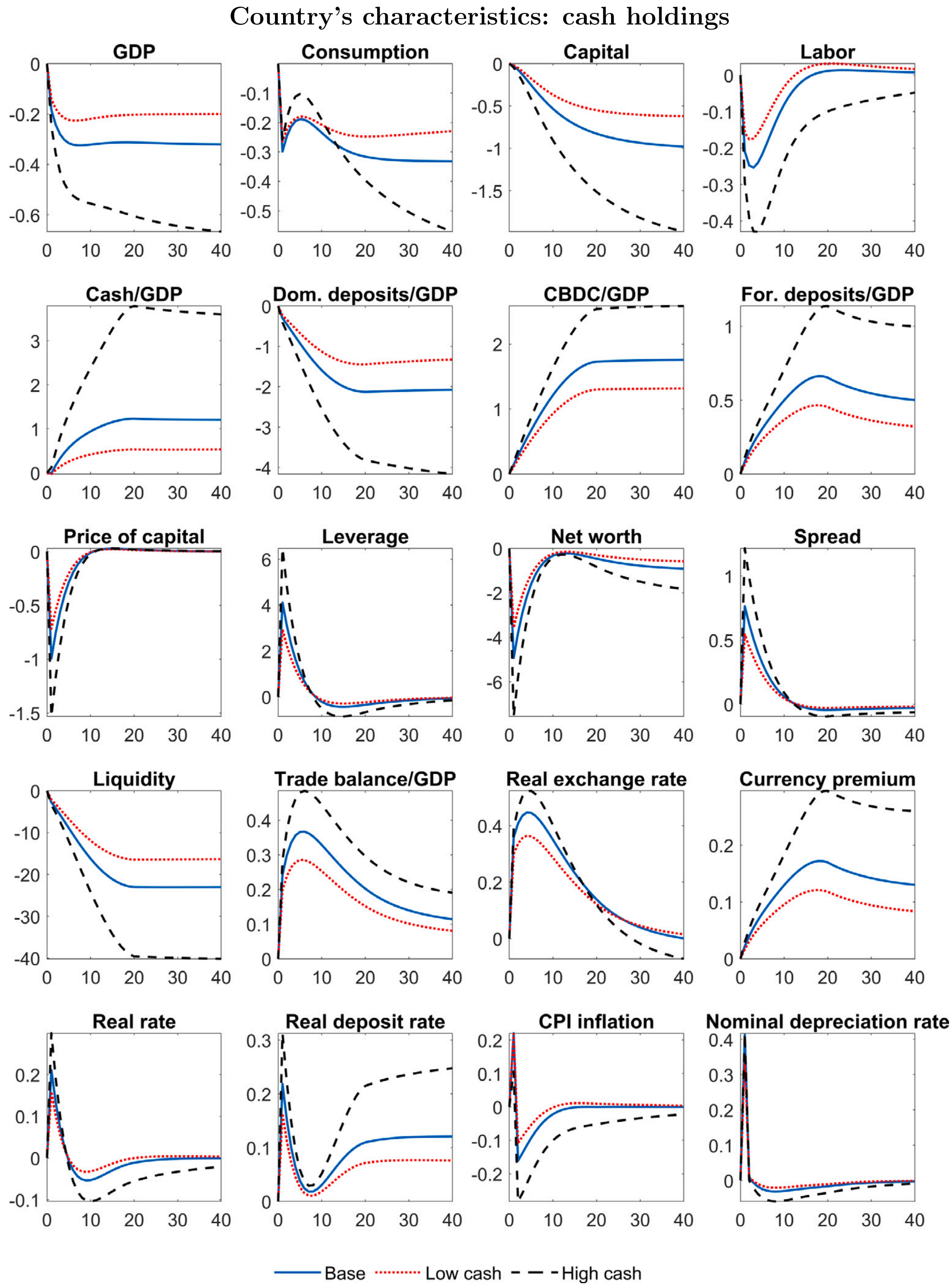

Fig. C.8. Gradual increase in the CBDC weight $\bar{\kappa}_M^* = 10\%$ in the deposit-like scenario ($\psi = 0$, $\bar{\kappa}_D$ gradually decreases). In period 0 the economy is in the steady state, in period 1 the transition begins. Blue solid line: baseline scenario ($m/4gdp = 7.4\%$). Red dotted line: low level of cash holdings ($m/4gdp = 5\%$). Black dashed line: high level of cash holdings ($m/4gdp = 10\%$).

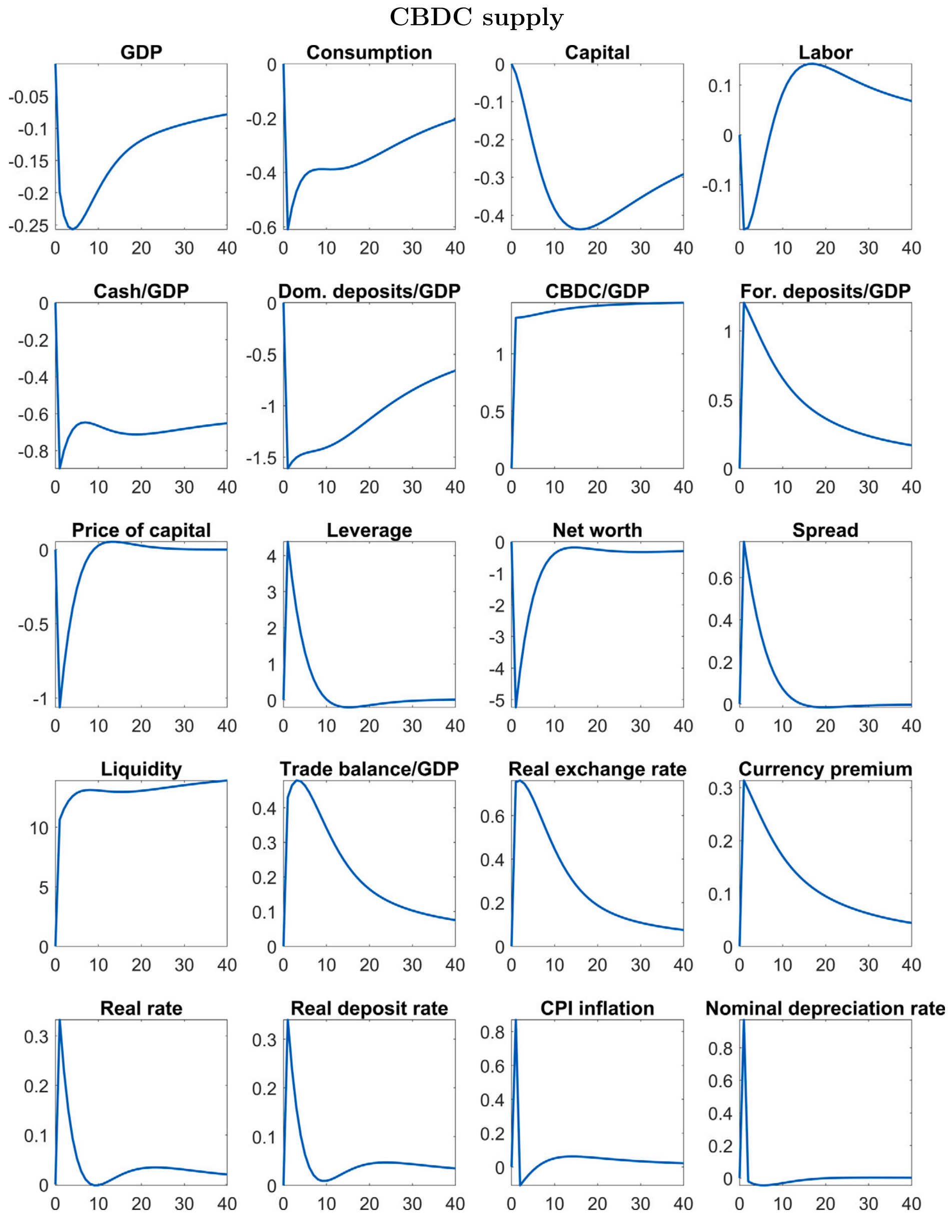

Fig. C.9. Shock to the supply of the foreign CBDC. In period 0 the CBDC tax is such that households do not invest in CBDC ($\tau_t^O = 0.24$ and $m_t^* = 0$). From period 1 on, we set $\tau_t^O = 0$.

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