Central Bank Digital Currency in Small Open Economies

Rong Fan[*] Todd B. Walker[†] Allan Wright[‡]

July 13, 2024

Abstract

This paper examines how the introduction of Central Bank Digital Currency (CBDC) impacts small open economies (SOE). We build a Two-Agent New Keynesian (TANK) model with financially constrained agents, where both cash and CBDC provide liquidity service. CBDC lowers the cost of carrying liquid assets but does not provides anonymity like cash. Our main results are: (i) CBDC always increases the welfare of financially unconstrained households; however, it increases the welfare of constrained households when the cost of carrying cash is high enough and when the government purchase level is sufficiently low; (ii) CBDC increases the fiscal income by bringing more agents out of the informal economy, improving fiscal sustainability; (iii) CBDC improves the terms of trade as it strengthens the domestic currency.

Keywords: CBDC, Fiscal policy, digital currency,

JEL Classification: J24, J31, O11, O14

[*]Department of Economics, Indiana University, fanrong@iu.edu
[†]Department of Economics, Indiana University, walkertb@indiana.edu
[‡]Central Bank of The Bahamas, ASWright@centralbankbahamas.com

1 Introduction

Central Bank Digital Currency (CBDC) has drawn immense attention and interest over recent years. Several countries have adopted CBDC (The Bahamas, Jamaica, Nigeria, etc.) or are testing CBDCs in pilot projects (Sweden, China, etc.). Questions abound concerning the benefits and costs of CBDC and the extent to which economies will be impacted by its introduction.

The most direct benefit is that CBDC provides financial services at a much lower transaction cost, promoting financial inclusion by providing households and businesses with a convenient and safe way of payment. Murakami et al. (2022) show that CBDC can help unbanked households to smooth consumption. CBDC can also minimize underground economic activities and help the government better understand the economy. The government can enforce fiscal policy more efficiently, and the central bank can extract additional information from CBDC transactions, which might be vital to changes in policy. Kwon et al. (2022) show that CBDC can remove the inefficiency associated with tax evasion that serves to improve the fiscal position of the country (see also, Burlon et al., 2022).

On the other hand, CBDC introduces new risks and challenges. First, given that CBDC might act as a substitute for bank deposits and serve to compete with the banking sector (Bindseil, 2020), it could lead to financial instability. It remains unclear to what extent the lack of competition in the banking sector can be improved through CBDC issuance (Kim and Kwon, 2023). Second, CBDC can only promote financial inclusion and lowers the transaction cost when the financially constrained households have enough incentive to adopt it (Ozili, 2022). The introduction of CBDC requires careful design to not obstruct the functioning of the banking system (Bindseil, 2020). Ren et al. (2022) show that the anonymity design of CBDC presents unique challenges.

We argue here that the benefits of CBDC might disproportionately fall to small open economies (SOE), as SOEs face unique challenges. SOEs in general, do not have a well-established and efficient payment systems; many households are still unbanked and rely heavily on cash (even foreign currency). It is costly for households to get, carry, and pay with cash. The monopoly power of the banking sector lowers the capacity of the bank to provide accessible financial services to households. SOEs are also heavily exposed to international financial shocks since they are price takers on the international market and face a volatile capital inflow/outflow. The Global Findex Database (Worldbank, 2021) buttresses many of these claims. Consider that in developing economies, only about 40 percent of adults who paid utility bills (18 percent of adults) did so directly from an financial account. And only bout half of adults in developing economies could access extra funds within 30 days if faced with an unexpected expense.

The goal of this paper is to evaluate how CBDC could impact small open economies. First, we measure how much the adoption of CBDC can improve social welfare. While current adoption rates remain low, we ask if / when adoption rates improve, what will be the resultant changes to the economy. While adotpion rates are endogenous in our model, we do not seek to benchmark current adoption rates to steady state as we believe steady state has not been achieved. CBDC can promote financial inclusion by providing financially constrained households with a better way to save. Second, CBDC can improve the terms of trade and increase domestic purchase power. Third, CBDC can improve fiscal policy implementation by minimizing underground economic activities, so we quantify how much the adoption of CBDC can increase fiscal policy.

This paper delivers mainly two results. First, adopting CBDC always increases financially unconstrained households' welfare. However, it increases the welfare of financially constrained households only when the cost of carrying cash is high enough and the government purchase level is sustainable. CBDC provides a better way of saving for financially constrained households and decreases the deadweight loss of carrying and transporting cash. However, the tax burden of constrained households increases as CBDC decreases the underground economy. The net welfare change of constrained households depends on the magnitude of the tax burden. With a better and stronger financial institution, the terms of trade improve, and domestic households experience an improvement in the standard of living. Second, the adoption of CBDC minimizes underground economies. The government can collect consumption tax more easily and efficiently as CBDC loses the anonymity property of cash. The government is able to collect more tax income with the use of CBDC. In other words, the government can maintain a sustainable debt level by imposing a lower consumption tax rate. A lower consumption tax rate lowers the distortion and increases economic efficiency.

1.1 Connection with the Literature

The welfare implications of CBDC have drawn extensive attention in the recent literature. CBDC opens new opportunities but also brings new challenges to monetary policy. This paper makes mainly two contributions. First, we focus on the small open economies and discuss how CBDC affects the terms of trade. Second, we study how CBDC affects fiscal policy effectiveness.

This paper makes four main contributions to the current CBDC literature. First, this paper studies the welfare and policy implications of CBDC by developing a DSGE model with financially constrained households. This paper is similar to Barrdear and Kumhof (2016), where they build a large-sized closed economy DSGE model with monetary transaction costs. They concludes that CBDC increases the steady state output by 3%. Both Barrdear and Kumhof (2016) and George et al. (2020) argue that CBDC as a secondary monetary policy instrument could substantially improve the central bank's ability to stabilize the business cycle. However, the presence of a CBDC amplifies the international spillovers by adding additional non-arbitrage conditions (Ferrari et al., 2020).

Second, this paper is related to the literature on financial inclusion. CBDC provides a better and easier way to save and serves as a good way for the general population to start using financial services. Financial inclusion can generate a significant amount of public revenue in taxes and decrease poverty levels and income inequality. In contrast, financial literacy, innovation, and technology are critical success factors in achieving financial inclusion outcomes (Ozili, 2021). Gali et al. (2004) develop the standard benchmark model to study financial inclusion. Limited asset market participation increases the volatility and decreases the stability of the economy (Bilbiie(2008)). Wage stickiness (Ascari et al. (2011) and Colciago (2011)) and consumption habits (Motta and Patrizio, 2010) are two most important channels that reshape the impulse response functions dramatically. Mehrotra and Yetman(2014) extended the basic framework of Gali et al.(2004) by characterizing optimal monetary policy. Higher financial inclusion decreases both output volatility and inflation volatility due to increased inter-temporal substitution but increases the optimal ratio between the variances of output and inflation. The contribution of this paper is to extend this benchmark model into a small open economy setup. Most of the conclusions from the literature still hold, but the welfare implications are affected by the country's international position (terms of trade, foreign debt).

Third, this paper borrows the small open economies setup from the literature, mainly the small open economy version of the Calvo sticky price model developed by Gali and Monacelli (2005). There are other ways to set up an open economy. Laxton and Pesenti (2003) develop a two-country version of the Global Economic Model (GEM). De Paoli (2009) develops a two-country version of the Calvo sticky price model, taking the home country size limit to zero. The utility-based loss function can be written as a quadratic expression of domestic inflation, output gap, and real exchange rate. The optimal policy rule implies lower real exchange rate volatility or a domestic inflation-targeting regime depending on the elasticity of substitution between domestic and foreign goods.

The non-competitive banking sector is an important modeling choice and borrows from several papers. When the banking sector is competitive enough, CBDCs crowd out bank deposits. However, as long as CBDC increases the overall welfare, the CBDC adoption can be Pareto improving as the crowding out can be neutralized by proper monetary policy (Gross and Schillerb, 2020). At the same time, CBDC can decrease the demand for cash and crowd in the banking sector when the banking sector is not competitive and efficient enough (Andolfatto, 2021). The effects of CBDC on the banking sector depend on several factors, e.g., interest rate and functions of CBDC. Chiu et al. (2019) introduce entrepreneurs and bankers to the money search model. They find that CBDC competes with checkable deposits and can crowd out or crowd in the private sector depending on the CBDC interest rate. Williamson et al., 2019 argue that it's also important to consider the functions of CBDC. If CBDC is introduced as a substitute for physical currency, the CBDC interest rate needs to be sufficiently low to avoid a narrow bank regime. If CBDC is issued through a narrow banking arrangement, CBDC can relax the collateral constraints of banks. Productivity can also play a role when determining the effects of CBDC on the banking sector. Cash-like digital currency is a perfect substitute for physical currency. Deposit-like digital currency crowds out bank deposits when productive projects are abundant, which is desirable if productive projects are sufficiently scarce (Keister and Sanches, 2021).

In the rest of this paper, we start by setting up the model in section 2. Then we discuss the proper calibration of the model in section 3. In sector 4, welfare implications are shown, along with plots of the variance decompositions using the calibration in section 3.

2 Model

The model is an extension of the Two-Agent, New Keynesian (TANK) model (Gali et al. (2004) and Gali and Monacelli (2005)) to small open economies allowing for trade dynamics and an exogenous foreign sector. Financially constrained households face transactions costs and liquidity shocks that are ameliorated by central bank digital currency. The foreign sector is treated as exogenously given, and the foreign output and interest rate both follow an exogenous autoregressive process.

2.1 Households (HHs)

Consumption is a convex combination of domestic, c_{Ht}, and foreign goods, c_{Ft},

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

where the share-parameter $\gamma \in [0,1]$ governs the extent of home bias and η determines the elasticity of substitution. The representative household decides how to allocate her consumption expenditure between domestic and foreign goods through a static optimization problem that delivers,

$$c_{Ht} = \gamma \left(\frac{P_{Ht}}{p_t} \right)^{-\eta} \qquad c_{Ft} = (1-\gamma) \left(\frac{P_{Ft}}{p_t} \right)^{-\eta} \tag{1}$$

where p_t is the domestic Consumer Price Index (CPI), i.e., the price of one unit of consumption, $p_t = \left[\gamma P_{Ht}^{1-\eta} + (1-\gamma) P_{Ft}^{1-\eta} \right]^{\frac{1}{1-\eta}}$. The price of the foreign good coincides with the foreign CPI p_t^*, adjusted by the nominal exchange rate e_t, $P_{Ft} = e_t p_t^*$. The real exchange rate is the ratio of the foreign and domestic price levels, where the foreign price level is converted into domestic currency units via the nominal exchange rate, $\xi_t = e_t \frac{p_t^*}{p_t}$. If we define $p_{Ht} = P_{Ht}/p_t$ and $p_{Ft} = P_{Ft}/p_t$ as the price of domestic and foreign goods in terms of the domestic CPI, then the real exchange rate can be written as, $\xi_t = p_{Ft}$, and the terms of trade, i.e., the ratio between the price imports and the price exports is given by

$$tot_t = \frac{P_{Ft}}{P_{Ht}} = \frac{\xi_t}{p_{Ht}} \tag{2}$$

UNCONSTRAINED HHS ($1-\lambda$) Unconstrained households, in measure $1-\lambda$, choose consumption c_{1t} and labor supply h_{1t}, receiving labor income ω_t; pay a consumption tax, τ_c, and receive a lump-sum transfer from the government t_{1t}, and profits of intermediate firms and banks, Γ_{1t}.

Unconstrained households have access to financial services and receive liquidity from commercial banks. There is a continuum measure of monopolistically competitive banks indexed by $j \in [0,1]$. Bank deposits are substitutes with the elasticity of substitution $\epsilon_b > 1$, as $\epsilon_b \to \infty$ the banking sector becomes perfectly competitive. The total liquidity for unconstrained households can be written as:

$$l_{1t} = \int_0^1 (d_{1t}(j)^{\frac{\epsilon_b - 1}{\epsilon_b}} dj)^{\frac{\epsilon_b}{\epsilon_b - 1}} \tag{3}$$

The return $r_t^d(j)$ to bank deposits d_{1t} is determined by the bank sector optimization problem to be discussed below. Unconstrained households also hold a one-period domestic government bond b_{1Ht} and foreign bond b_{1Ft}, with return r_t and r_t^*, respectively. Households pay a quadratic adjustment cost when they change their financial position (foreign bond and foreign currency) with the rest of the world; this assumption ensures the existence of a determinate steady state and a stationary solution (see, Schmitt-Grohé and Uribe (2003)).

The unconstrained households' problem can be written in real terms as:

$$\max_{c_{1t}, h_{1t}, l_{1t}, d_{1t}(j), b_{1Ht}, b_{1Ft}} E_0 \sum_0^\infty \beta^t \left(\frac{c_{1t}^{1-\sigma}}{1-\sigma} - \chi \frac{h_{1t}^{1+\phi}}{1+\phi} \right),$$

subject to the budget and liquidity constraints:

$$(1+\tau_c)c_{1t} + \int_0^1 (d_{1t}(j) - \frac{r_{t-1}^d(j)}{\pi_t} d_{1t-1}(j)) dj + (b_{1Ht} - \frac{r_{t-1}}{\pi_t} b_{1Ht-1}) + \xi_t (b_{1Ft} - r_{t-1}^* b_{1Ft-1})$$
$$\leq w_t h_{1t} + t_{1t} + \Gamma_{1t} - \frac{\kappa_B}{2} \xi_t ((1-\lambda) b_{1Ft} - \bar{b}_F)^2$$
$$l_{1t} = \int_0^1 (d_{1t}(j)^{\frac{\epsilon_b - 1}{\epsilon_b}} dj)^{\frac{\epsilon_b}{\epsilon_b - 1}}$$

CONSTRAINED HH (λ) The constrained households, in measure λ, do not have access to financial services. They choose consumption c_{2t} and labor supply h_{2t}, receiving income ω_t, and a lump-sum transfer from the government t_{2t}.

Following Schmitt-Grohé and Uribe (2004), we assume consumption purchases are subject to a proportional transactions cost, s_{2t}, that depend on the households access to financial services and is given by the functional form,

$$s_{2t} = z_t A_2 \frac{c_{2t}}{l_{2t}} + B_2 \frac{l_{2t}}{c_{2t}} - 2\sqrt{A_2 B_2} \tag{4}$$

The variable l_{2t} represents household access to liquidity and is one of the defining characteristics distinguishing constrained from unconstrained households. Unconstrained households have access to financial services and receive liquidity from commercial banks. The functional form of (4) implies a transaction cost that is decreasing in the liquidity ratio l_{2t}/c_{2t} as long as the following condition is satisfied, $\frac{c_{2t}}{l_{2t}} > \sqrt{\frac{B_2}{z_t A_2}}$, where A_2 and B_2 are parameters of the s_{2t} function. The process z_t is a liquidity demand shock that follows an autoregressive process,

$$\log(z_t) = \rho_z \log(z_{t-1}) + \nu_t^z, \quad \nu_t^z \sim N(0, \sigma_z^2)$$

which we interpret as an unanticipated change in transaction costs.

Constrained households can only get liquidity service by holding cash (m_{2t}) and/or CBDC ($CBDC_{2t}$). A critical feature of our model is how CBDC compares to cash. We make two assumptions along these lines that we state explicitly.

Assumption 1: Anonymity of Cash. Households transacting in cash do not pay the consumption tax.

While it is *not* the case that CBDC will allow governments to link transactions to households, cash affords total anonymity. In our model, we assume the benefit of this anonymity is the ability to avoid the consumption tax. Obviously, the benefits of anonymity extend beyond avoiding a single tax; however, we believe this modeling assumption adequately captures the (perhaps perceived) cost associated with switching from cash to CBDC.

Assumption 2: Convenience & Safety of CBDC. Cash users face an additional cost δ_m of transacting since it is less convenient and less safe.

Acquiring and carrying cash is costly in many small open economies. Digital wallets have proven to be secure and as more vendors accept digital currencies, the relative benefits of CBDC will continue to expand. Thus, we view CBDC as a more convenient and safer alternative, and model this as a cost imposed on cash users.

Finally, we assume that cash and CBDC are substitutes with the elasticity of substitution

$\epsilon_m > 1$. The calibration of this parameter can be viewed as directly influencing the ratio of circulating CBDC to cash. The higher elasticity, the higher the adoption rate of CBDC and hence, the lower the amount of cash in circulation. The total liquidity for constrained households can be written as, $l_{2t} = ((m_{2t})^{\frac{\epsilon_m - 1}{\epsilon_m}} + (CBDC_{2t})^{\frac{\epsilon_m - 1}{\epsilon_m}})^{\frac{\epsilon_m}{\epsilon_m - 1}}$.

The constrained households' problem is given by

$$\max_{c_{2t}, h_{2t}, l_{2t}, m_{2t}, CBDC_{2t}} E_0 \sum_0^\infty \beta^t \left(\frac{c_{2t}^{1-\sigma}}{1-\sigma} - \chi \frac{h_{2t}^{1+\phi}}{1+\phi} \right)$$

subject to the budget and liquidity constraints:

$$\begin{aligned} \text{s.t.} \quad & \left(1 + s_{2t} + \tau_c \frac{CBDC_{2t}}{l_{2t}}\right) c_{2t} + (m_{2t} - \frac{1-\delta_m}{\pi_t} m_{2t-1}) + (CBDC_{2t} - \frac{1}{\pi_t} CBDC_{2t-1}) \\ & \leq w_t h_{2t} + t_{2t} \\ & l_{2t} = ((m_{2t})^{\frac{\epsilon_m - 1}{\epsilon_m}} + (CBDC_{2t})^{\frac{\epsilon_m - 1}{\epsilon_m}})^{\frac{\epsilon_m}{\epsilon_m - 1}} \\ & s_{2t} = z_t A_2 \frac{c_{2t}}{l_{2t}} + B_2 \frac{l_{2t}}{c_{2t}} - 2\sqrt{A_2 B_2} \end{aligned}$$

2.2 Banking Sector

There is a continuum measure of monopolistically competitive banks, $j \in [0,1]$, that take deposits from unconstrained households $d_t(j)$ and invest in intermediate firms $i_t(j)$ and accumulate capital stock $k_t(j)$. The deposit demand functions are solved from the household problem above,

$$d_t(j) = \left(\frac{(r_t - r_t^d(j))^{-\epsilon_b}}{\left(\int_0^1 (r_t - r_t^d(j))^{1-\epsilon_b} dj\right)^{-\frac{\epsilon_b}{1-\epsilon_b}}} \right) d_t$$

Banks are owned by unconstrained households and maximize expected pre-dividend profits,

$$\max_{r_t^d(j), i_t(j), k_t(j)} E_0 \sum_0^\infty \beta^t \frac{\lambda_{1t}}{\lambda_{10}} \left(r_t^k k_{t-1}(j) - i_t(j) + (d_t(j) - \frac{r_{t-1}^d(j)}{\pi_t} d_{t-1}(j) \right),$$

where λ_1 is the stochastic discount factor of the unconstrained household. The maximization is subject to the law of motion of capital and balance sheet constraint: $k_t(j) = (1-\delta)k_{t-1}(j) + \left(1 - \frac{\kappa_I}{2}\left(\frac{i_t(j)}{i_{t-1}(j)} - 1\right)\right) i_t(j)$, where there is an adjustment cost to investment and market clearing gives, $k_t(j) = d_t(j)$. First-order conditions yield the optimal deposit rate chosen by the banks,

$$r_t^{d*} = \frac{\epsilon_b}{\epsilon_b - 1} \frac{\beta E_t \lambda_{1t+1}(r_{t+1}^k + (1-\delta)q_{t+1}) - (q_t - 1)\lambda_{1t}}{\beta E_t(\lambda_{1t+1}/\pi_{t+1})} - \frac{1}{\epsilon_b - 1} r_t.$$

where q is the price of the investment good. Note that $\epsilon_b \to \infty$ yields a perfectly competitive banking sector and the deposit rate chosen by the bank becomes the net return to capital:

$$r_t^{d*} = \frac{\beta E_t \lambda_{1t+1}(r_{t+1}^k + (1-\delta)q_{t+1}) - (q_t - 1)\lambda_{1t}}{\beta E_t(\lambda_{1t+1}/\pi_{t+1})}.$$

In this scenario, the banking sector would not exist and funds would flow directly to firms from households.

2.3 Firms

The firms' problems are standard and therefore our discussion will be brief. The representative final-good firm uses a CES aggregator to produce the domestic final good, and the intermediate firms produce differentiated domestic inputs. The final-good firm maximizes,

$$\max_{y_{Ht}, y_{Ht}(i)} \quad P_{Ht}(\int_0^1 y_{Ht}(i)^{\frac{\epsilon}{\epsilon-1}})^{\frac{\epsilon-1}{\epsilon}} - \int_0^1 P_{Ht}(i) y_{Ht}(i)$$

First-order conditions give the demand for intermediate goods, $y_{Ht}(i) = y_{Ht}\left(\frac{P_{Ht}(i)}{P_{Ht}}\right)^{-\epsilon}$. The intermediate good firms, indexed by i, produce a differentiated domestic input using the following Cobb-Douglas function, $y_{Ht}(i) = a_t(k_{t-1}(i))^{\alpha}(h_t(i))^{1-\alpha}$, where a_t is the total factor productivity, which follows an autoregressive process:

$$\log(a_t) = (1-\rho_a)\log(\bar{a}) + \rho_a \log(a_{t-1}) + \nu_t^a, \quad \nu_t^a \sim N(0, \sigma_a^2)$$

Firms operate in monopolistic competition, so they set the price of their own goods subject to the demand of final good firms. In addition, firms pay quadratic adjustment cost $AC_t(i)$ in nominal terms as in Rotemberg (1982), whenever they adjust prices with respect to the benchmark inflation rate $\bar{\pi}$:

$$AC_t(i) = \frac{\kappa_P}{2}\Big(\frac{P_{Ht}(i)}{P_{Ht-1}(i)} - \bar{\pi}\Big)^2 P_{Ht} y_{Ht}$$

2.4 Policy

The government finances public expenditure g_t and transfers τ_{1t} and τ_{2t} with a consumption tax, by issuing public debt and with seigniorage revenue from money and CBDC holdings:

$$p_{Ht} g_t + (1-\lambda) t_{1t} + \lambda t_{2t} = (1-\lambda)(b_{1t} - \frac{r_{t-1}}{\pi_t} b_{1t-1}) + \lambda(m_{2t} - \frac{1}{\pi_t} m_{2t-1} + CBDC_{2t} - \frac{1}{\pi_t} CBDC_{2t-1})$$
$$+ (1-\lambda)\tau_c c_{1t} + \lambda \tau_c \frac{CBDC_{2t}}{l_{2t}} c_{2t} \quad (5)$$

where public expenditure g_t follows an autoregressive process: $\log(g_t) = (1-\rho_g)\log(\bar{g}) + \rho_g log(g_{t-1}) + \nu_t^g$, $\nu_t^g \sim N(0, \sigma_g^2)$. The central bank sets the nominal interest rate following a Taylor rule:

$$\frac{r_t}{\bar{r}} = \left(\frac{r_{t-1}}{\bar{r}}\right)^{\rho_r} \left(\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi} \left(\frac{p_{Ht}y_{Ht}}{\overline{p_H y_H}}\right)^{\phi_y} \left(\frac{\Delta e_t}{\overline{\Delta e}}\right)^{\phi_e}\right)^{1-\rho_r} \exp(\nu_t^m)$$

where $\nu_t^m \sim N(0, \sigma_m^2)$ is a monetary policy shock. The policy rate responds to steady-state deviations in inflation, an output gap, and changes in the exchange rate.

2.5 Foreign Sector As is standard in small-open economies, the foreign sector is treated as exogenous. Foreign output y_t^* and interest rate r_t^* follow the autoregressive processes:

$$\log(y_t^*) = \rho_y \log(y_{t-1}^*) + \nu_t^y, \quad \nu_t^y \sim N(0, \sigma_y^2)$$
$$r_t^* = (1-\rho_r)\frac{1}{\beta} + \rho_r r_{t-1}^* + \nu_t^r, \quad \nu_t^r \sim N(0, \sigma_r^2)$$

The foreign CPI is assumed to be constant over time, $\pi^* = \frac{p_t^*}{p_{t-1}^*} = 1$. Given the home bias γ^* of the foreign country, the demand for domestic goods x_t of the foreign sector is $x_t = \gamma^* \left(\frac{p_{Ht}}{s_t}\right)^{-\eta} y_t^*$.

3 Calibration

Our calibration consists of standard parameters that are well established in the small open economy literature (Table 1) and non-standard parameters that are set to match steady state values (Table 2), such as the parameters associated with cash and CBDC, fiscal and monetary policy targets, and the openness of the economy. We view the parameters in Table 2 more as median values of Bayesian priors. Posterior analysis is not possible given the dearth of data available on CBDC. Therefore, our results will vary these parameters over a broad range (i.e., diffuse posterior) and calculate statistics that are well established.

Table 1 presents the parameter values sourced from the literature. The standard parameters of the New Keynesian model in SOEs such as the elasticity of substitution between domestic and foreign goods η are calibrated using Gali and Monacelli (2015). Price adjustment cost κ_P is set to be 60 to be consistent with the probability of setting a new price to 0.25. We used Gertler and Karadi (2011) to calibrate the parameters related to the production sector, such as capital depreciation rate δ and investment adjustment cost κ_I. The calibration of shock parameters is taken from George et al. (2020), where they used data from New Zealand.

Table 2 presents parameter values calibrated to match certain steady state moments and are considered our baseline calibration. However, we will vary these values over a broad range to better understand the dynamics of the model. Therefore, while Table 1 is a dogmatic prior

	Description	Value	Reference
Household			
β	Discount factor	0.99	Gali and Monacelli (2015)
σ	Intertemporal elasticity of substitution	2	Beaudry and van Wincoop (1996)
χ	Leisure weight	1	Gali and Monacelli (2015)
ϕ	Frisch elasticity	3	Gali and Monacelli (2015)
Firm			
α	Capital share	0.33	Gali and Monacelli (2015)
κ_P	Price adjustment cost	60	Gali and Monacelli (2015)
ϵ	Intermediate-good elasticity of substitution	6	Gali and Monacelli (2015)
δ	Capital depreciation rate	0.025	Gertler and Karadi (2011)
κ_I	Investment adjustment cost	1.728	Gertler and Karadi (2011)
Shock parameters			
ρ_a	a autocorrelation	0.8552	George et al. (2020)
ρ_z	z autocorrelation	0.7217	George et al. (2020)
ρ_g	g autocorrelation	0.8	George et al. (2020)
σ_a	Standard deviation of a innovation	0.00711	George et al. (2020)
σ_z	Standard deviation of z innovation	0.00694	George et al. (2020)
σ_g	Standard deviation of g innovation	0.05	George et al. (2020)
σ_m	Standard deviation of m innovation	0.025	George et al. (2020)
SOE			
η	Domestic and foreign good ES	2	Gali and Monacelli (2015)
$\bar{y}^*$	Foreign output	1	Normalized
$\bar{r}^*$	Foreign bond interest rate	$1/\beta$	Normalized
ρ_{y^*}	y^* autocorrelation	0.6031	George et al. (2020)
ρ_{r^*}	r^* autocorrelation	0.5374	George et al. (2020)
σ_{y^*}	Standard deviation of y^* innovation	0.0788	George et al. (2020)
σ_{r^*}	Standard deviation of r^* innovation	0.0799	George et al. (2020)

Table 1: Parameters Directly Calibrated from Literature

that we will not alter, Table 2 can be thought of as median values for the prior that generate a diffuse posterior range of values. For example, while The Bahamian Sand Dollar was launched in October 2020, adoption rates remain low. We are not interested in the current welfare gain of CBDC given current adoption rates, but how might the economy *evolve* if CBDC is more widely adopted. Thus, the purpose of this paper is to provide a laboratory that can be used to understand uncertainties about CBDC implementation. We examine low, medium and high adoption rates in the following sections. After analyzing the main results using a benchmark calibration, we will implement sensitivity checks to understand the results relative to different calibrations for parameters in Table 2. We will focus on the CBDC adoption rate, the welfare gain, and the volatility change as parameter values to be varied. The sensitivity check exercise will help us to predict the effects of CBDC under different scenarios and for a broad range of countries.

Government bond $\bar{B}$ and purchases $\bar{G}$ are calibrated to match the public debt and GDP ratio and public spending and GDP ratio in small open economies (e.g., The Bahamas). Domestic

	Description	Value	Implied steady state	Value
Household				
λ	Share of constrained households	20%	Share of unbanked households	20%
δ_m	Cost of carrying cash	0.1	Time spent on getting cash	
ϵ_m	Cash-CBDC elasticity of substitution	2	CBDC adoption rate	
A	Transaction cost function	0.9	Cost of transaction	
B	Transaction cost function	0.7	Money velocity	1.25
Monetary: Taylor rule				
$\bar{r}$	Taylor rule: interest rate target	$\bar{\pi}/\beta$	Nominal interest rate	
$\bar{\pi}$	Taylor rule: inflation target	1	Inflation rate	1
$\overline{\Delta e}$	Taylor rule: real exchange rate target	1	Exchange rate	1
ρ_r	Interest rate elasticity	0.6		
ϕ_π	Inflation elasticity	5		
ϕ_y	Output elasticity	10		
ϕ_e	Exchange rate elasticity	10		
Fiscal				
ρ_C	Consumption tax persistence	0.8		
ϕ_C	Consumption tax adjustment to debt	5		
τ_C	Target consumption tax	0.12	Average consumption tax	0.12
$\bar{B}$	Government bond/GDP ratio	0.8	National debt/GDP	80%
$\bar{G}$	Government purchase/GDP ratio	0.1	Government purchase/GDP	10%
ρ_T	Transfer payment persistence	0.9		
ϕ_T	Transfer/GDP ratio	0.05	Transfer/GDP	5%
Open economy				
γ	Domestic home bias	0.58	Import/GDP ratio	42.13%
γ^*	Foreign home bias	0.27	Export/GDP ratio	27.49%
$\bar{B}_F$	Steady state foreign bond level	0.05	Financial account balance/GDP	0.05
κ_B	Foreign bond adjustment cost	2	Financial account volatility	

Table 2: Parameters with Implied Steady State Implications

and foreign home bias γ and γ^* are calibrated to match the openness of the economy, i.e., the import-GDP ratio and the export-GDP ratio. $\bar{B}_F$ is calibrated to match the financial account balance. The ratio of constrained households λ is assumed to be 20% at baseline. This is a conservative estimate for countries like The Bahamas and Jamaica as it does not include "under" banked households or households that have limited access to financial services. The cost of carrying cash δ_m, consumption tax τ_C and Cash-CBDC elasticity of substitution ϵ_m jointly determine the CBDC adoption rate. The CBDC adoption rate is increasing in the cost of carrying cash δ_m (benefit of CBDC) and decreasing in the consumption tax τ_C (cost of CBDC). The elasticity of substitution ϵ_m affects how sensitive the adoption rate responds to the benefit and cost of CBDC. The amount of liquidity the households hold (money velocity) depends on the transaction function, it is increasing in the ratio B_2/A_2. The transaction cost (dead-weight loss associated with liquidity constraint) is increasing in A_2 and B_2.[1]

[1] Schmitt-Grohe and Uribe (2004) calibrate A and B using U.S. data from 1960:1 to 1999:3 to get A = 0.0111 and B = 0.07524. We believe our higher estimates are justified for small open economies. As a check, we vary these parameters for nearly all of the results discussed below and do not get substantially different results.

4 Results

Our results suggest the introduction of CBDC into small-open economies like The Bahamas has important implications for welfare and equilibrium dynamics. Our current analysis is a steady-state assessment of welfare under alternative parameter specifications.

	no CBCD	with CBDC
Consumption	1.1280	1.1353
Labor	0.6977	0.6893
Capital	16.9156	16.7474
Investment	0.4229	0.4187
GDP	1.7229	1.7058
Government bond	0.9361	0.9195
Consumption (unconstrained)	1.1381	1.1453
Labor (unconstrained)	0.6690	0.6594
Consumption (constrained)	1.0875	1.0952
Labor (constrained)	0.8123	0.8089
Cash	1.1518	0.2399
CBDC	0	0.4012
Transaction cost	0.0037	0.0002
Cost of carrying cash	0.1152	0.0240
Domestic price	0.8623	0.8636
Real exchange rate	1.2828	1.2790
Consumption tax	0.2633	0.2408
Tax revenue	0.2397	0.2374

Table 3: Steady State Comparison

4.1 Welfare gains

The steady state of the economy with and without CBDC is presented in Table 3. After CBDC is introduced, constrained households adopt CBDC and decrease the use of cash. Both household types increase their consumption level while decreasing labor supply. Due to the higher domestic savings rate, the real exchange rate decreases, and terms of trade improve. Most importantly, the government can impose a lower consumption tax to maintain fiscal sustainability, which decreases the tax distortion. The consumption tax falls by two percentage points while revenues barely change.

Next we calculate consumption-equivalent welfare. We report the welfare costs as percent of consumption equivalents. For example, to compare two different policy regimes, say A and B, we measure how much consumption households are willing to give up under policy regime A to be indifferent between both policy regimes. More precisely, $100 \times \lambda^c$ measures the percentage of the consumption stream that agents are willing to forgo under policy regime A in order to be as well off as under policy regime B. Formally, we solve for λ^c in the following set of equations:

$$V_0^A = E_0 \sum_{t=0}^{\infty} \beta^t \left[((1-\lambda^c)\frac{c_t^{A,1-\sigma}}{1-\sigma}) - \chi \frac{h_t^{A^{1+\phi}}}{1+\phi} \right] \quad (6)$$

$$\lambda^c = 1 - \exp\{(V_0^B - V_0^A)(1-\beta)\}. \quad (7)$$

We examine steady state values (V_0^A and V_0^B) with and without CBDC, and then solve for the corresponding λ^c. The social or aggregate welfare is increased by 0.0505 with the unconstrained improving 0.0594 and constrained 0.0323. Thus, CBDC increases the welfare of constrained households in steady state by decreasing the dead weight loss associated with the use of cash. Although they need to pay more consumption tax when using CBDC, the benefits of adopting CBDC outweigh the costs. Second, CBDC provides a better and easier way to save compared with cash; constrained households can therefore better insure against domestic and foreign shocks using savings. The welfare of unconstrained households also improves because CBDC promotes financial inclusion and increases overall domestic savings. The real exchange rate decreases, and the terms of trade improve. Second, unconstrained households benefit from the lower consumption tax rate, as CBDC helps the government to collect consumption tax more efficiently and decreases distortions. These indirect channels are important for assessing the welfare of unconstrained households, which we discuss further below.

When we analyze the welfare implications of CBDC, the two most important variables are the share of constrained households, which is determined by parameter λ, and the CBDC adoption rate, which is jointly determined by the cost of carrying cash δ_m and elasticity of substitution between cash and CBDC ϵ_m. The consumption tax rate τ_C and CBDC adoption rate are highly correlated. One of our primary takeaways is the importance of fiscal variables. A higher consumption tax dramatically decreases the CBDC adoption rate, while a low CBDC adoption rate forces the government to increase the tax rate in order to maintain government debt stability.

Figure 1 presents the change of welfare and equilibrium consumption tax revenue as the share of constrained households (λ), the cost of carrying cash (δ_m), and the elasticity of substitution between cash and CBDC (ϵ_m) change. Social welfare is increasing in the share of constrained households λ, and the cost of carrying cash δ_m with the introduction of CBDC. The benefit of financial inclusion increases as the share of constrained households λ increases. The reduction in dead-weight loss increases as the cost of carrying cash δ_m increases. An interesting insight from this figure is that the cost of carrying cash is a much more sensitive parameter with respect to welfare. The welfare of the constrained is nearly monotonically increasing in the cost of carrying cash and is much more responsive to this parameter vis-a-vis the elasticity. This is

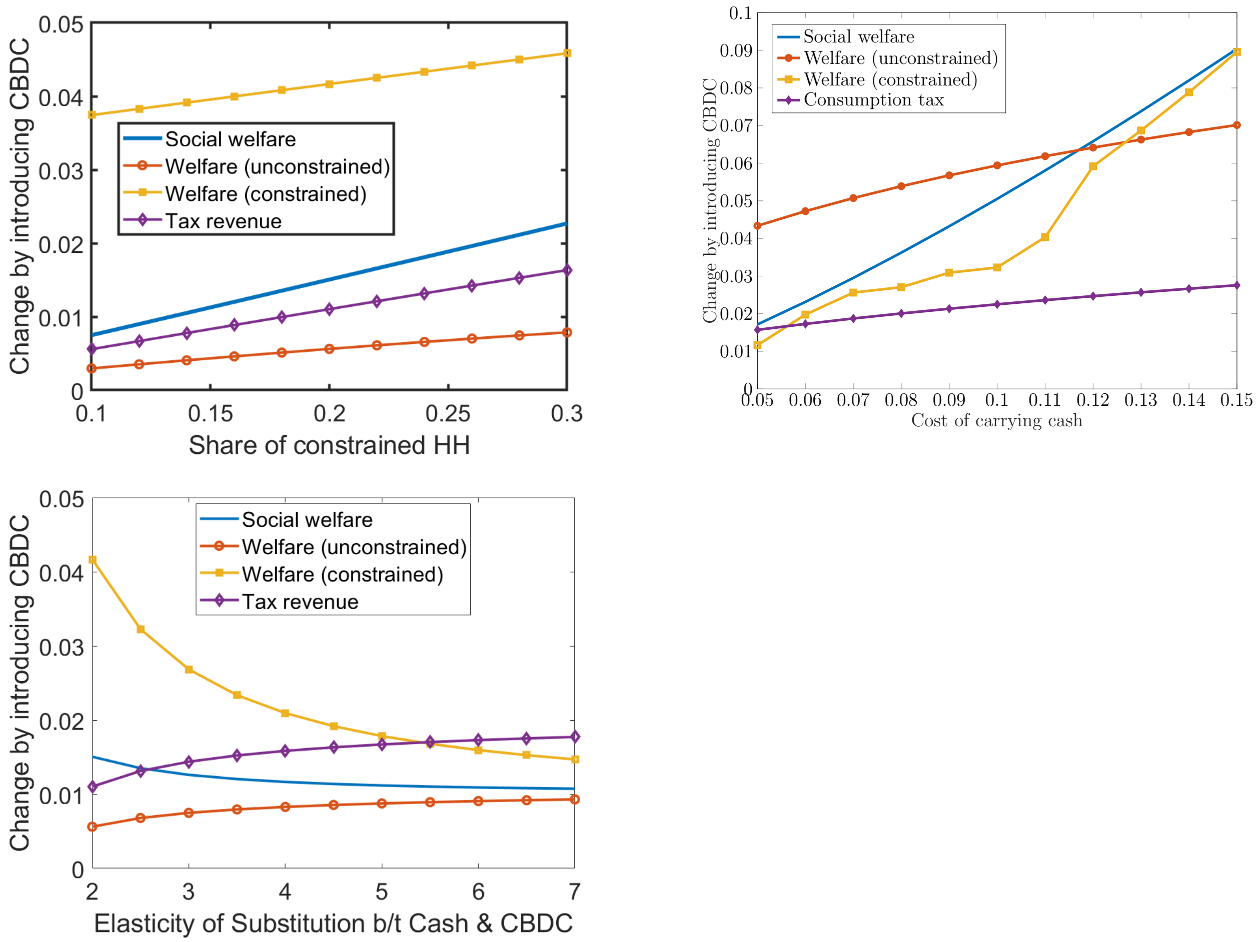

Figure 1: Change of Steady State by Introducing CBDC

Notes: Change of steady state as the parameters change. The change in welfare is computed by the consumption equivalence. The change in tax revenue is the difference between the tax revenue after and before introducing CBDC.

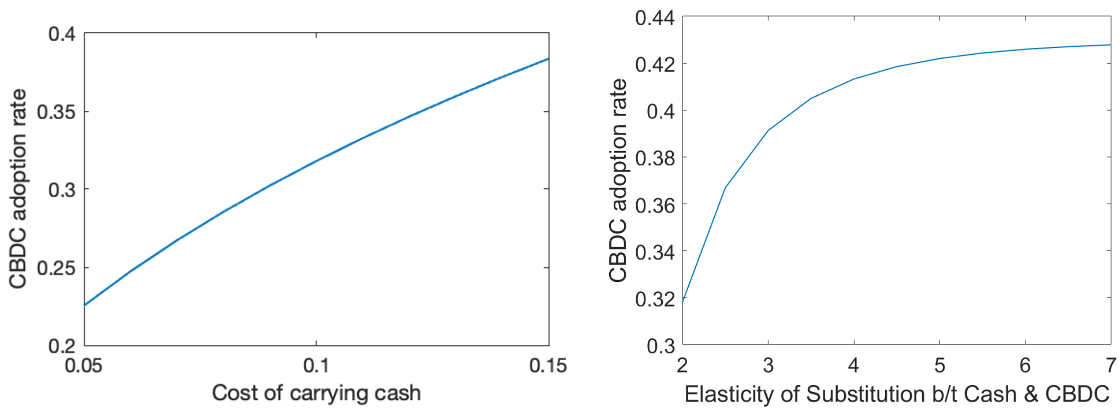

Figure 2: CBDC Adoption Rate

Notes: CBDC adoption rate as the parameters change. CBDC adoption rate is defined as the ratio between CBDC and total liquidity.

due to the convenience outweighing the benefits of anonymity at thes parameter values, which suggests that reducing the cost of carrying cash should be a priority for policy makers.

Figure 2 presents the CBDC adoption rate as a function of the cost of carrying cash and elasticity of substitution between cash and CBDC. CBDC adoption rate increases in both situations and more aggressively over the paramter range for carrying cash. As a result, the equilibrium consumption tax rate τ_C decreases more after introducing CBDC, which is why unconstrained households benefit from the adoption of CBDC. The elasticity of substitution between cash and CBDC ϵ_m also matters. The social welfare gain decreases as the elasticity of substitution between CBDC and cash ϵ_m increases. Constrained households can benefit more from adopting CBDC when ϵ_m is smaller, i.e., cash and CBDC are more complementary. Unconstrained households, on the other hand, benefit less from adopting CBDC when cash and CBDC are more complementary

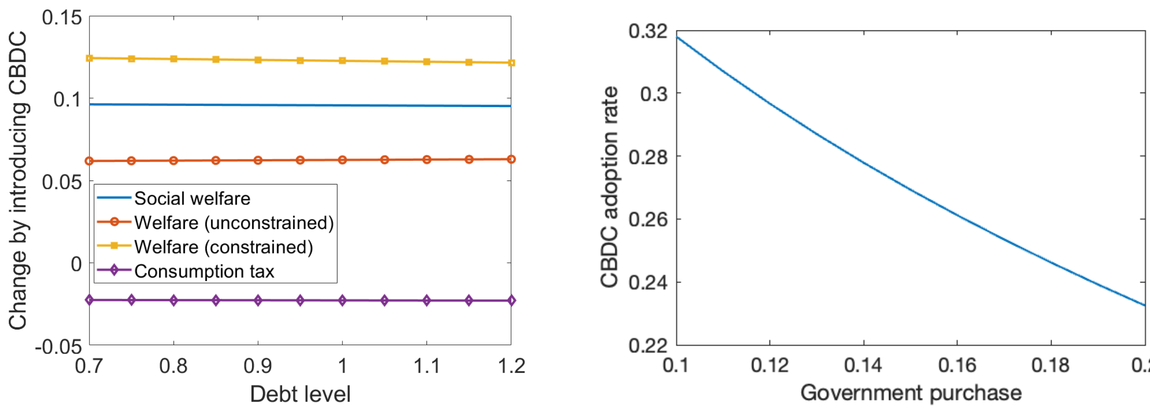

Figure 3: Change of Steady State and CBDC Adoption Rate

Notes: Change of steady state as the parameters change. The change in welfare is computed by the consumption equivalence. The change in tax revenue is the difference between the tax revenue after and before introducing CBDC. CBDC adoption rate as the parameters change. The CBDC adoption rate is defined as the ratio between CBDC and total liquidity.

One aspect of the model that is novel is the emphasis on fiscal policy. Steady state government purchases have a significant impact on welfare. The government needs to charge a higher consumption tax to offset the higher government purchase $\bar{G}$. Constrained households face a higher cost when adopting CBDC. The left panel of Figure 3 presents the change of welfare and equilibrium consumption tax as steady state government spending, $\bar{G}$, changes. The right panel of Figure 3 presents the CBDC adoption rate as $\bar{G}$ changes. The social welfare gain from adopting CBDC decreases as government purchases increase. As government purchases increase, the government imposes a higher consumption tax, which decreases the CBDC adoption rate. The overall welfare gain will be lower since CBDC is not widely used. The constrained households have less welfare gain when the government purchase is higher because they must pay a higher consumption tax when using CBDC. The unconstrained households have more welfare gain when the government purchase is higher as the marginal gain from the tax evasion is higher when the original rate is higher.

4.2 Variance Decompositions

The previous section focuses on steady state values and this section analyzes the interaction of CBDC and shocks. We are mainly interested in the variance decomposition of consumption and labor supply of constrained households since they are affected the most by the CBDC adoption. Consumption is directly related to household welfare, and the labor supply is an important channel to explain these dynamic changes.

The first parameter we investigate is the share of constrained households, λ. The share of constrained households is an important statistic because as this number increases, the total labor supply is much more volatile. Constrained households rely heavily on adjusting labor supply to smooth consumption, as opposed to adjusting savings. These households benefit from CBDC adoption because it allows them to smooth using financial assets.

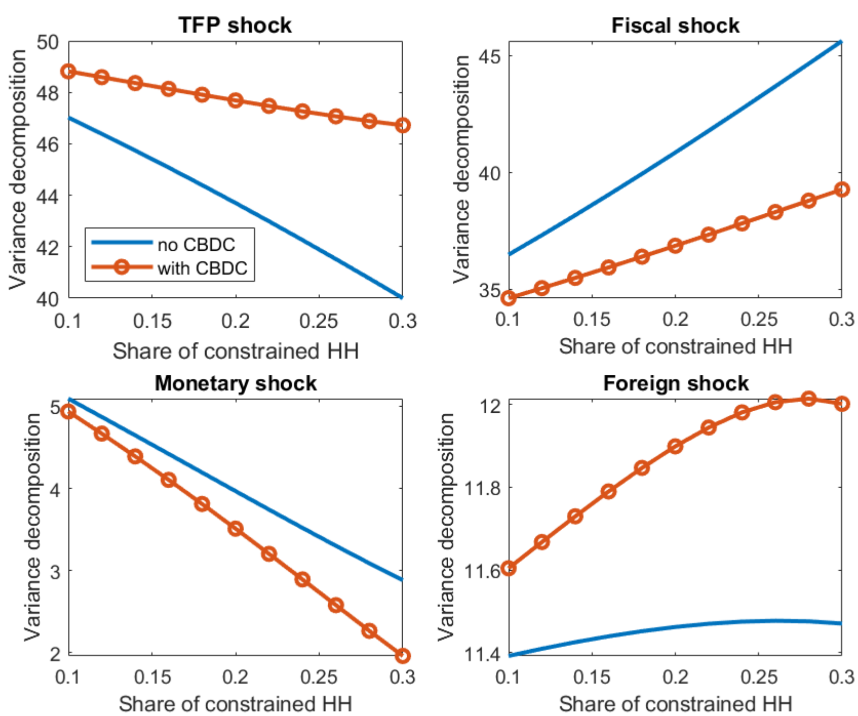

Figure 4: Variance Decomposition of Consumption (unconstrained) as λ Changes

Figure 4 presents the variance decomposition of consumption of unconstrained households as the share of constrained households λ changes. CBDC increases the impact of TFP shocks on the consumption of unconstrained households but decreases the contribution of fiscal and monetary shocks. The constrained households increase their labor supply following a negative TFP shock, and a higher labor supply dampens the impact of a negative TFP shock. After CBDC is adopted, they increase their labor supply less. As is standard, the consumption of unconstrained households is more affected by TFP shocks. The impact of CBDC is increasing in the share of constrained households λ, as more households are affected by CBDC.

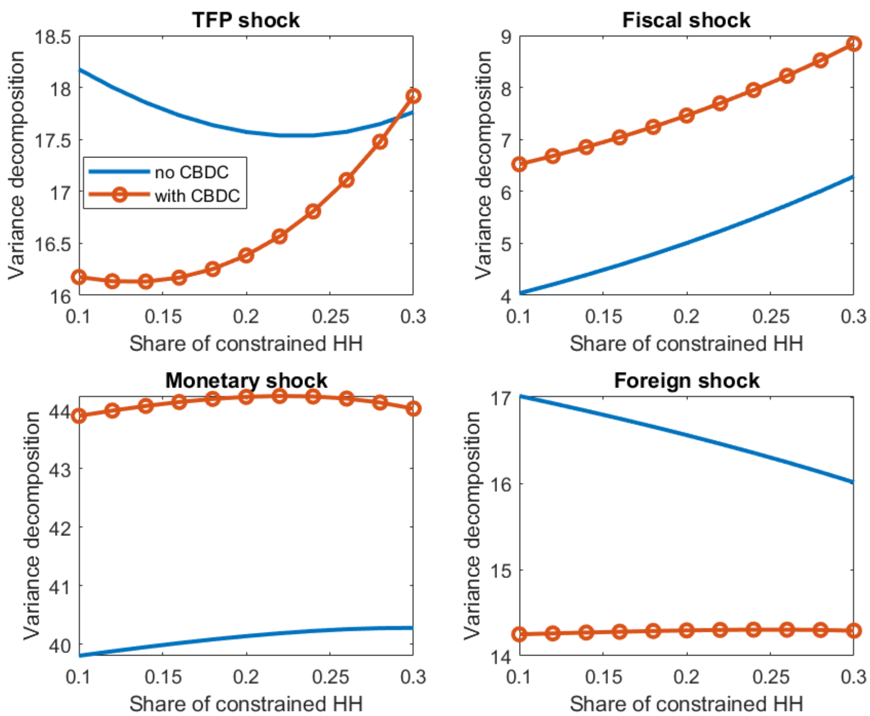

Figure 5: Variance Decomposition of Consumption (constrained) as λ Changes

Figure 5 presents the variance decomposition of consumption of constrained households as the share of constrained households λ changes. CBDC decreases the impact of TFP shocks on the consumption of constrained households but increases the contribution of fiscal and monetary shocks. CBDC decreases the impact of TFP shocks as it promotes financial inclusion and helps unconstrained households to smooth their consumption. The impact of CBDC is decreasing in the share of constrained households λ. This figure gives a sense in which financial inclusion alters the impact of productivity. As the share of unconstrained households falls, the variance decomposition associated with the TFP shock falls by over 10 percent.

Figure 6 presents the variance decomposition of labor supply of constrained households as the share of constrained households λ changes. The importance of TFP shocks decreases as the share of constrained households λ increases. The labor supply of the constrained households responds more to TFP shocks when the share of constrained households is small, as the wage

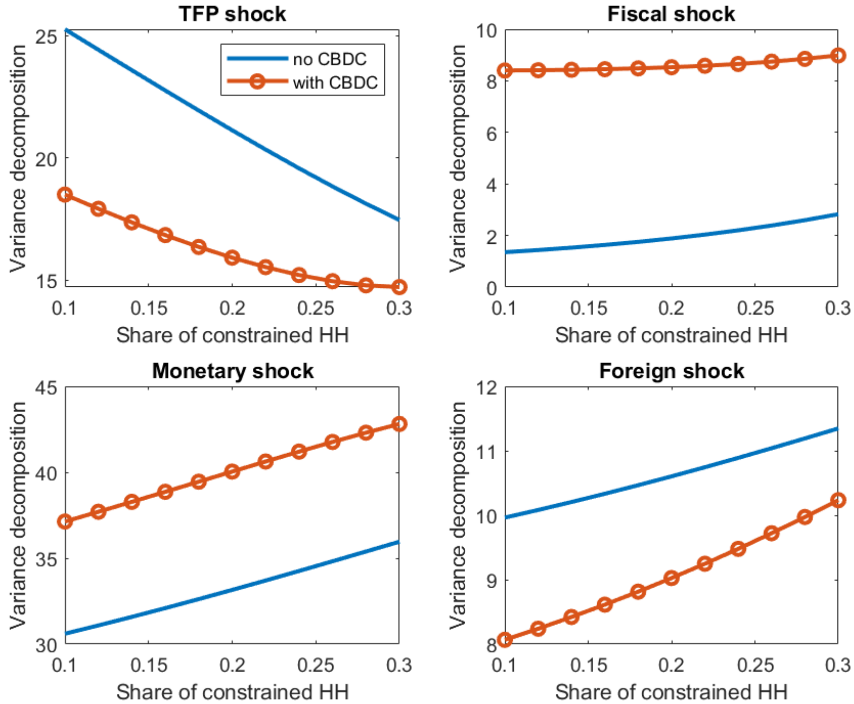

Figure 6: Variance Decomposition of Labor Supply (constrained) as λ Changes

does not decrease much as the constrained households increase their labor supply. The change of variance decomposition is robust with different λ values.

The second parameter we investigate is the cost of carrying cash δ_M. This parameter determines the CBDC adoption rate, as more CBDC will be adopted as the cost of carrying cash increases. This parameter also affects the welfare effect of CBDC substantially, as the welfare benefit of CBDC is higher when the cost of carrying cash is higher. Figure 7 presents the variance decomposition of consumption of unconstrained households as the cost of carrying cash δ_m changes. The contribution of TPF shocks to consumption variance is increasing in δ_m but decreases after CBDC has been introduced. Without CBDC, the cost of cash amplifies TFP shocks, since cash is not an ideal way of saving. With CBDC, higher δ_m motivates the households to hold more CBDC and helps the households to smooth out the consumption.

Figure 8 presents the variance decomposition of consumption of constrained households as the cost of carrying cash δ_m changes. The contribution of TPF shocks to consumption variance is increasing in δ_m when CBDC hasn't been introduced but decreases in δ_m after CBDC has been introduced. Without CBDC, the cost of cash amplifies TFP shocks, since cash is not an ideal way of saving. With CBDC, higher δ_m motivates the households to hold more CBDC and helps the households to smooth out the consumption.

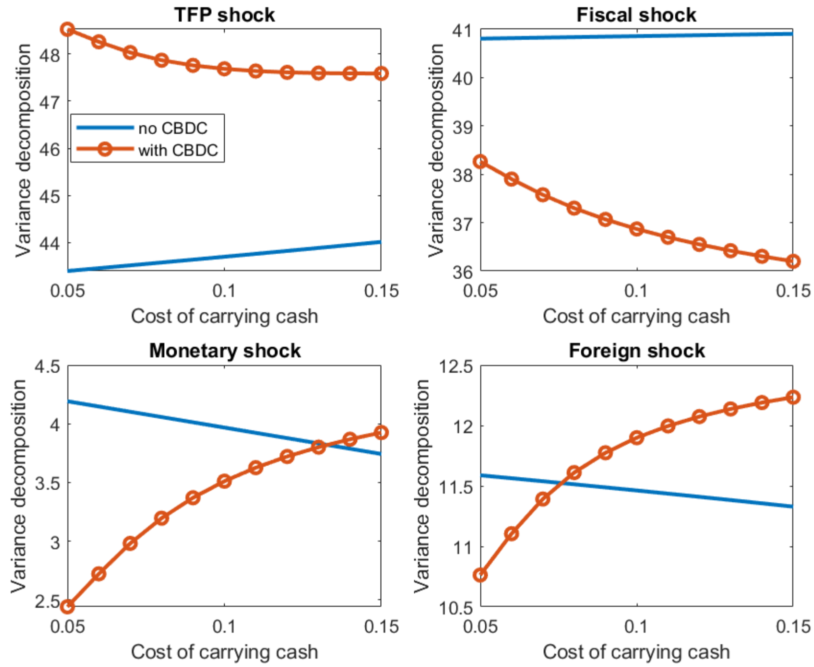

Figure 7: Variance Decomposition of Consumption (unconstrained) as δ_m changes

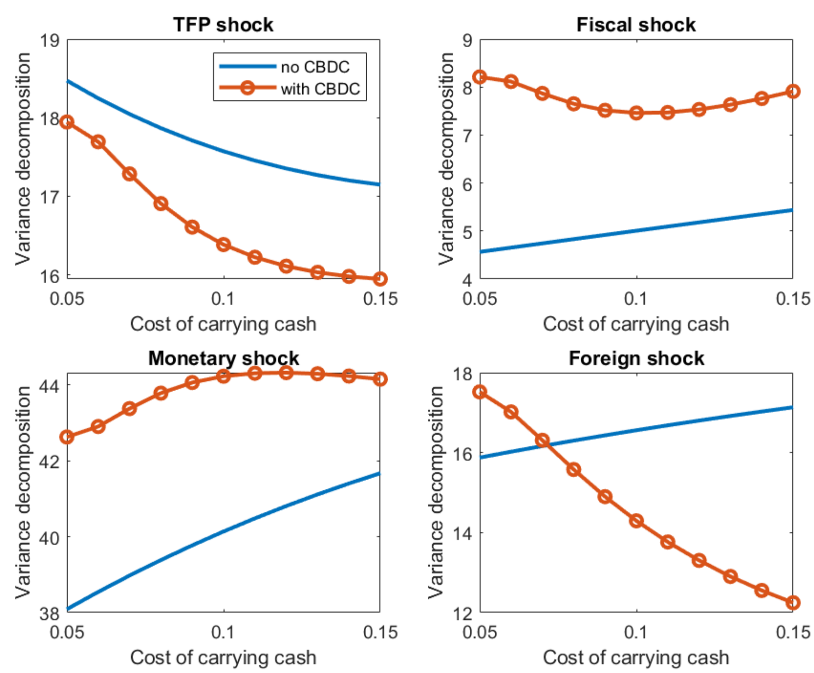

Figure 8: Variance Decomposition of Consumption (constrained) as δ_m changes

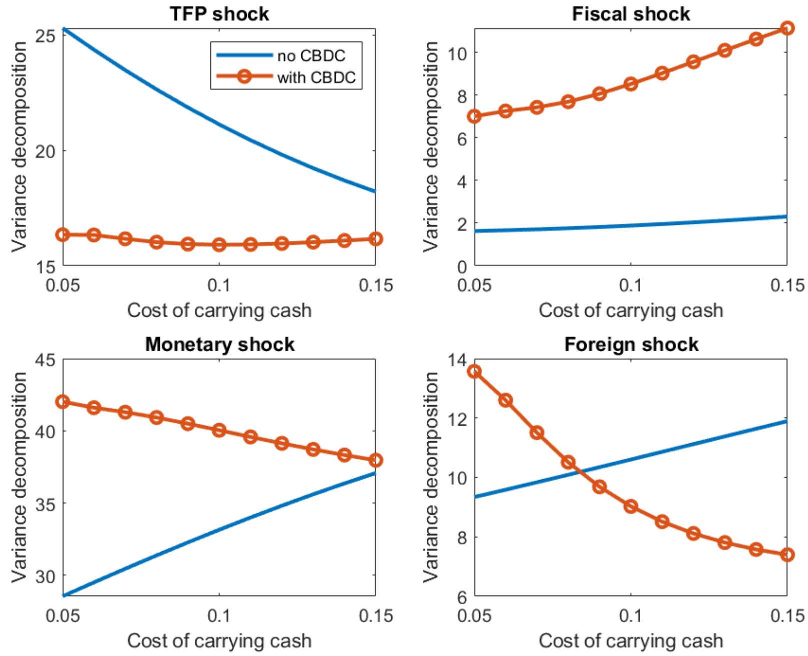

Figure 9: Variance Decomposition of Labor Supply (constrained) as δ_m Changes

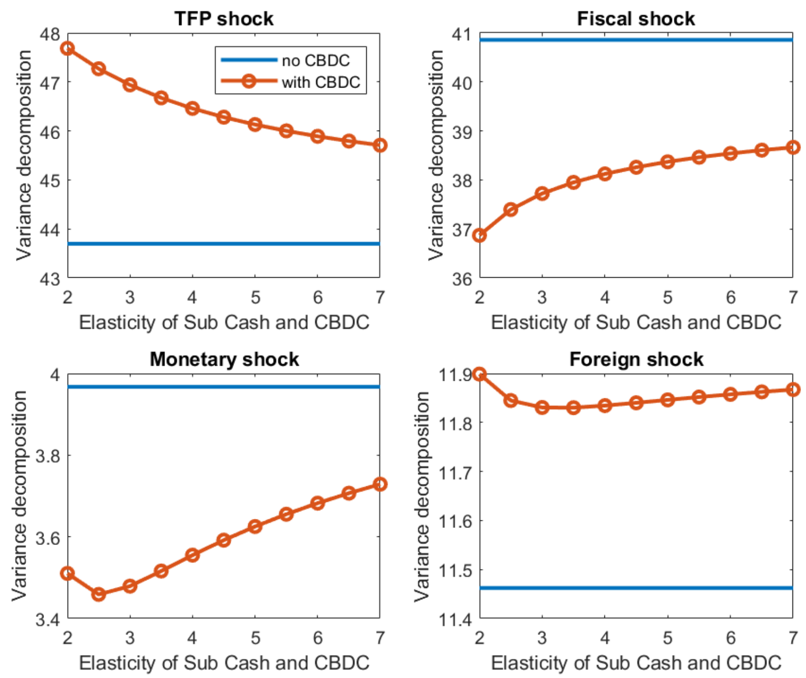

Figure 10: Variance Decomposition of Consumption (unconstrained) as ϵ_m changes

The CBDC adoption rate is increasing not only in the cost of carrying cash δ_m but also in the elasticity between cash and CBDC ϵ_m. As a result, the parameter we investigate is the elasticity between cash and CBDC ϵ_m. Figure 10 presents the variance decomposition of consumption of unconstrained households as the elasticity between cash and CBDC ϵ_m changes. ϵ_m does not have an effect when CBDC is not introduced. With CBDC, unconstrained households are less affected by TFP shock as the elasticity between cash and CBDC ϵ_m increases. When cash and CBDC are less complementary, unconstrained households increase more their labor supply with a negative TFP shock. The higher labor supply helps the unconstrained households to have a higher return to capital and insure against the TFP shock.

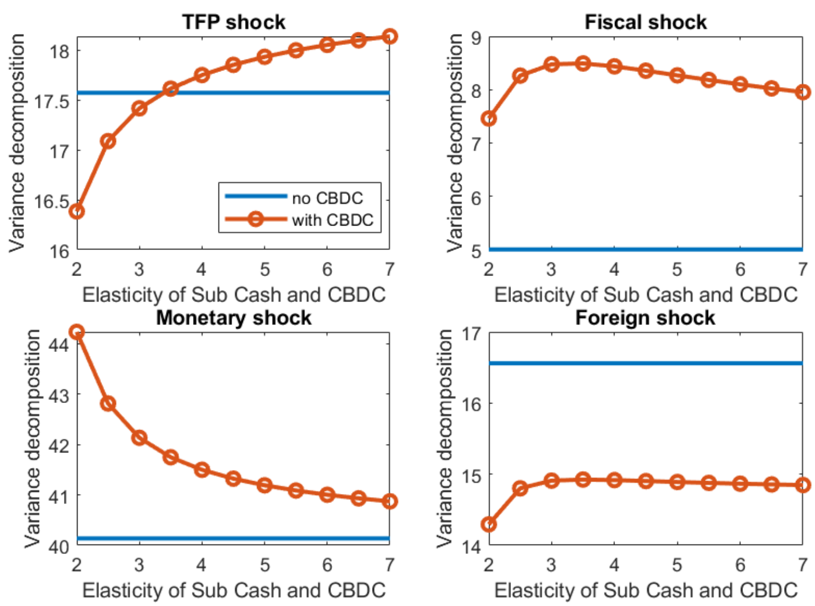

Figure 11: Variance Decomposition of Consumption (constrained) as ϵ_m changes

Figure 11 presents the variance decomposition of consumption of constrained households as the elasticity between cash and CBDC ϵ_m changes. With CBDC, constrained households are more affected by TFP shocks as the elasticity between cash and CBDC ϵ_m increases. When cash and CBDC are less complementary, constrained households benefit less from CBDC and are less insured against the TFP shocks.

5 Concluding Thoughts and Extensions

There are many potential costs and benefits to a CBDC. Dynamic, stochastic, general equilibrium models provide a laboratory to assess these potential costs and benefits. In this paper, we have highlighted several frictions that would materialize more readily in developing economies.

However, there are important extensions that one can consider, in particular, dollarization and a further reduction in the competitiveness of the banking sector. For example, one can consider a banking sector that has monopoly power with banks setting a lower rate for deposit to maximize their profit. The financial market is thus inefficient since a lower deposit rate lowers the incentive for households to save. One could analyze how CBDC interacts with banks when the banking sector is inefficient. When CBDC pays interest rates, it increases the banking sector's competitiveness and drives up the deposit rate. Monopolistic banks need to increase their deposit rate to compete with the central bank over household savings. Under this scenario, the competitiveness of the banking sector increases. CBDC crowds in the banking sector and increases the supply of deposits/investments. The second extension one could consider is dollarization. Financially constrained households use both domestic currency (and CBDC if introduced) and the US dollar in their transaction; the deposit can be indexed both in domestic currency and the US dollar. We anticipate that adoption of CBDC lowers the use of the US dollar and decreases the degree of dollarization. Households choose to hold CBDC instead of dollar due to its safety and convenience. As the level of dollarization decreases, the country can implement monetary policy more efficiently and improve its terms of trade. Finally, we note that adoption costs for CBDC are nontrivial. Poor financial literacy and limited access to basic financial services implies that government-backed adoption rates could be lower than optimal. We leave these extensions to future work.

References

Andolfatto, David, "Assessing the impact of central bank digital currency on private banks," *The Economic Journal*, 2021, *131* (634), 525–540.

Ascari, Guido, Andrea Colciago, and Lorenza Rossi, "Limited asset market participation: does it really matter for monetary policy?," *Bank of Finland research discussion paper*, 2011, (15).

Barrdear, John and Michael Kumhof, "The macroeconomics of central bank issued digital currencies," 2016.

Beaudry, Paul and Eric van Wincoop, "The Intertemporal Elasticity of Substitution: An Exploration using a US Panel of State Data," *Economica*, 1996, *63* (251), 495–512.

Bilbiie, Florin O, "Limited asset markets participation, monetary policy and (inverted) aggregate demand logic," *Journal of economic theory*, 2008, *140* (1), 162–196.

Bindseil, Ulrich, "Tiered CBDC and the financial system," *Available at SSRN 3513422*, 2020.

Burlon, Lorenzo, Carlos Montes-Galdon, Manuel Muñoz, and Frank Smets, "The optimal quantity of CBDC in a bank-based economy," 2022.

Chiu, Jonathan, Seyed Mohammadreza Davoodalhosseini, Janet Hua Jiang, and Yu Zhu, "Bank market power and central bank digital currency: Theory and quantitative assessment," *Available at SSRN 3331135*, 2019.

Colciago, Andrea, "Rule-of-thumb consumers meet sticky wages," *Journal of money, credit and banking*, 2011, *43* (2-3), 325–353.

Ferrari, Massimo Minesso, Arnaud Mehl, and Livio Stracca, "Central bank digital currency in an open economy," 2020.

Gali, Jordi and Tommaso Monacelli, "Monetary policy and exchange rate volatility in a small open economy," *The Review of Economic Studies*, 2005, *72* (3), 707–734.

_, J David López-Salido, and Javier Vallés, "Rule-of-thumb consumers and the design of interest rate rules," 2004.

George, Ammu, Taojun Xie, and Joseph D Alba, "Central bank digital currency with adjustable interest rate in small open economies," *Available at SSRN 3605918*, 2020.

Gertler, Mark and Peter Karadi, "A model of unconventional monetary policy," *Journal of monetary Economics*, 2011, *58* (1), 17–34.

Grossa, Jonas and Jonathan Schillerb, "A model for central bank digital currencies: Do CBDCs disrupt the financial sector," *Available at SSRN*, 2020.

Keister, Todd and Daniel R Sanches, "Should central banks issue digital currency?," *Available at SSRN 3966817*, 2021.

Kim, Young Sik and Ohik Kwon, "Central bank digital currency, credit supply, and financial stability," *Journal of Money, Credit and Banking*, 2023, *55* (1), 297–321.

Kwon, Ohik, Seungduck Lee, and Jaevin Park, "Central bank digital currency, tax evasion, and inflation tax," *Economic Inquiry*, 2022, *60* (4), 1497–1519.

Laxton, Douglas and Paolo Pesenti, "Monetary rules for small, open, emerging economies," *Journal of Monetary Economics*, 2003, *50* (5), 1109–1146.

Mehrotra, Aaron N and James Yetman, "Financial inclusion and optimal monetary policy," 2014.

Motta, Giorgio, Patrizio Tirelli et al., "Rule-of-thumb consumers, consumption habits and the Taylor principle," Technical Report 2010.

Murakami, David, Ivan Shchapov, and Ganesh Viswanath-Natraj, "CBDCs, Financial Inclusion, and Monetary Policy," *Available at SSRN 4102397*, 2022.

Ozili, Peterson K, "Financial inclusion research around the world: A review," in "Forum for social economics," Vol. 50 Taylor & Francis 2021, pp. 457–479.

_ , "Can central bank digital currency increase financial inclusion? Arguments for and against," in "Big Data Analytics in the Insurance Market," Emerald Publishing Limited, 2022, pp. 241–249.

Paoli, Bianca De, "Monetary policy and welfare in a small open economy," *Journal of international Economics*, 2009, *77* (1), 11–22.

Ren, Diandian, Hongyu Guo, and Tingfeng Jiang, "Managed anonymity of CBDC, social welfare and taxation: A new monetarist perspective," *Applied Economics*, 2022, pp. 1–22.

Schmitt-Grohé, Stephanie and Martın Uribe, "Closing small open economy models," *Journal of international Economics*, 2003, *61* (1), 163–185.

_ **and** _ , "Optimal fiscal and monetary policy under sticky prices," *Journal of economic Theory*, 2004, *114* (2), 198–230.

Williamson, Stephen et al., "Central bank digital currency: Welfare and policy implications," *Unpublished, University of Western Ontario*, 2019, *4*.