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The Macroeconomic Effects of Different CBDC Regimes in an Economy with a Heterogeneous Household Sector*

Jana Anjali Magin† Ulrike Neyer‡ Daniel Stempel§

March 2023

Abstract

Many central banks discuss the introduction of a Central Bank Digital Currency (CBDC). Empirical evidence suggests that households may differ in their willingness to hold CBDC. Against this background, this paper investigates the macroeconomic effects of different CBDC regimes in a New Keynesian model with a heterogeneous household sector. We consider that a CBDC may facilitate transactions. In particular, households will face additional transaction costs if they do not hold their optimal mix of conventional forms of money and CBDC. We analyze the impact of four different CBDC regimes: (i) no CBDC, (ii) each household may hold an unlimited amount of CBDC, (iii) the central bank sets a maximum amount of CBDC each household is allowed to hold, (iv) the central bank uses the CBDC as a monetary policy instrument by adjusting the maximum amount of CBDC each household is allowed to hold. Generally, we find that the introduction of a CBDC increases economy-wide utility as it allows higher consumption. Moreover, the shock absorption capability increases in an economy with CBDC. This particularly applies to the case when the central bank uses the CBDC as a monetary policy instrument. By adjusting the maximum amount of CBDC, the central bank can stabilize prices more effectively after adverse shocks. However, this stabilization implies distributional effects between households.

JEL classification: E52, E42, E58, E41, E51.

Keywords: Central bank digital currency, monetary policy, household heterogeneity, central banks, New Keynesian model.

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1 Introduction

Central banks worldwide consider and debate the introduction of a Central Bank Digital Currency (CBDC). For instance, the European Central Bank (ECB) discusses the introduction of a digital euro but with a possible limit on CBDC holdings per household (Panetta, 2022). A CBDC is a digital form of money issued by a central bank. Generally, existing forms of digital central bank money, like reserves, are only available to financial institutions. Therefore, the central advantage of a CBDC is its accessibility. A Retail CBDC allows central banks to provide the broader public with a digital form of central bank money. This is particularly relevant due to the declining use of cash and an increasing demand for a secure, efficient and digital means of payment by citizens due to a changed shopping and payment behavior (Deutsche Bundesbank, 2021a; European Central Bank, 2023).[1] While demand for a CBDC exists (Bijlsma et al., 2021; Deutsche Bundesbank, 2021b), households differ in the extent to which they want to hold CBDC (Li, 2022).

Against this background, this paper investigates the macroeconomic effects of the introduction of four different CBDC regimes in a New Keynesian model, specifically considering that households differ in their preference for using CBDC. In the first regime ("no-CBDC regime"), no CBDC exists. In the second regime, each household may hold an unlimited amount of CBDC ("unconstrained regime"). In the third regime, each household may hold a limited amount of CBDC, i.e., the central bank sets a maximum amount of CBDC each household is allowed to hold ("constrained regime"). In the fourth regime, the central bank can use the CBDC limit as a monetary policy instrument ("MP regime"). Generally, the use of a CBDC facilitates specific transactions (Bordo and Levin, 2017). We capture this idea by introducing transaction costs into our model. If households are not able to hold their optimal mix of conventional forms of money (cash and bank deposits) and CBDC, they will face consumption reducing transaction costs. These transaction costs reflect higher costs for households if they cannot pay with their preferred means of payment.

We find that the introduction of a CBDC leads to higher economy-wide utility as it allows for an increase in consumption by facilitating transactions. Moreover, the shock absorption capability increases in an economy with CBDC after demand as well as supply

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[1] For an overview of the reasons for introducing a CBDC and design options see, for example, Bank for International Settlements (2018) and Roesl and Seitz (2022).

shocks. In addition, the central bank can stabilize prices more effectively when it uses the CBDC as a monetary policy instrument. By adjusting the CBDC limit, the central bank can affect transaction costs and thereby consumption in the economy, leading to a more effective attainment of price stability. In general, the introduction of a CBDC in a constrained manner and the use of the limit as a monetary policy instrument implies distributional effects across households.

This paper relates to the existing literature in the following ways. First, we contribute to the literature that develops DSGE models to analyze monetary policy effects of the introduction of a CBDC such as in Bacchetta and Perazzi (2021), George et al. (2020),Gross and Schiller (2021), Barrdear and Kumhof (2022), and Ferrari Minesso et al. (2022) by adding a heterogeneous household sector. Second, our paper is related to several papers on CBDC design and monetary policy. Respective examples are Bech and Garratt (2017), Bjerg (2017), Bordo and Levin (2017), Engert and Fung (2017), Mancini-Griffoli et al. (2018), Brunnermeier and Niepelt (2019), Allen et al. (2020), Uhlig and Xie (2020), Assenmacher et al. (2021), Borgonovo et al. (2021), Fernández-Villaverde et al. (2021), Kumhof and Noone (2021), Ahnert et al. (2022), Agur et al. (2022), Auer et al. (2022), and Davoodalhosseini (2022). We add to this strand of the literature by analyzing the effects of the utilization of a maximum amount of CBDC as a monetary policy instrument. Third, our paper relates to the literature that analyzes the effects of household heterogeneity and monetary policy in New Keynesian models as in Debortoli and Galí (2018) and Kaplan et al. (2018).[2] We contribute to these strands of the literature by analyzing the effects of the introduction and existence of a CBDC as well as the utilization of a CBDC limit as a monetary policy instrument in a setting with a heterogeneous household sector.

The paper is organized as follows. Section 2 describes the model. Section 3 details the model calibration and analyzes the results with regard to a demand and a supply shock. Section 4 concludes.

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[2] See Kaplan and Violante (2018) for a comprehensive overview.

2 Model

2.1 Households

The household sector in our model economy consists of two types of households $k = H, L$ ($-k$ denotes the respective other household), with household H being a household with high income and household L a household with low income. The share of H-households is κ, the share of L-households $1 - \kappa$. A household derives utility from consuming and disutility from working. Its respective periodic utility is given by

$$U_t^k = Z_t ln \left(C_t^k - \Psi^k C_{t-1}^k \right) - \chi \frac{{N_t^k}^{1+\eta^k}}{1 + \eta^k}, \tag{1}$$

where C_t^k is consumption, N_t^k is the number of hours worked, η^k the inverse Frisch elasticity of labor supply, and χ is a scaling parameter determining the weight of labor disutility. The parameter Ψ^k captures habit formation. Z_t is a demand shock following an AR(1) process. Consumption C_t^k is a composite consumption good described by the constant elasticity of substitution (CES) function

$$C_t^k = \left(\int_0^1 {c_{j,t}^k}^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}}, \tag{2}$$

where $c_{j,t}^k$ is the consumption of a specific variety j and θ is the elasticity of substitution between varieties. A household's expenditure minimization for a given level of consumption yields the optimal consumption of a variety j given by

$$c_{j,t}^k = \left(\frac{P_{j,t}}{P_t} \right)^{-\theta} C_t^k, \tag{3}$$

where $P_{j,t}$ is the price of variety j and $P_t \equiv \left(\int_0^1 P_{j,t}^{1-\theta} dj \right)^{\frac{1}{1-\theta}}$ is the overall price index.

Each household maximizes its discounted expected lifetime utility

$$\mathbb{E}_t \left[\sum_{\iota=0}^{\infty} \beta^\iota U_{t+\iota}^k \right], \tag{4}$$

subject to its budget constraint

$$P_t \zeta_t^k C_t^k + B_t^k = W_t^k N_t^k + (1 + i_{t-1}) B_{t-1}^k + D_t^k \tag{5}$$

with β denoting the discount factor. The left hand side (LHS) of the household's budget constraint shows its expenditures, consisting of its nominal expenditures for consumption $P_t \zeta_t^k C_t^k$ and for one-period, risk-free bonds B_t^k at price unity. The variable ζ_t^k reflects that transaction costs are potentially incurred. We will comment on these costs in more detail below. The right hand side (RHS) shows the household's nominal income, consisting of its labor income, where W_t^k denotes the nominal wage, of principal and interest payments of the bonds bought by the household in the period before, with i_t being the risk-free interest rate, and of dividends D_t^k resulting from the household's ownership of firms.

Households need money to buy consumption goods and to cover potential transaction costs, i.e., they face a money-in-advance constraint. Denoting a household's holdings of real money balances by m_t^k, this constraint is therefore given by

$$m_t^k = C_t^k \zeta_t^k . \tag{6}$$

A household has the possibility to hold conventional money (cash and deposits) and CBDC. We assume that each household wants to hold a specific mix of these two types of money. Denoting real conventional money holdings by $m_{C,t}^k$ and real CBDC holdings by $m_{CB,t}^k$, we capture the household's money holdings preference by the following CES function for a household's overall demand for real money balances

$$m_t^k = \left((\omega^k)^{\frac{1}{\varphi^k}} m_{C,t}^k{}^{\frac{\varphi^k - 1}{\varphi^k}} + (1 - \omega^k)^{\frac{1}{\varphi^k}} m_{CB,t}^k{}^{\frac{\varphi^k - 1}{\varphi^k}} \right)^{\frac{\varphi^k}{\varphi^k - 1}} , \tag{7}$$

where $0 \leq \omega^k \leq 1$ determines the weight on the demand for conventional money and $1 - \omega^k$ on the demand for CBDC respectively. The parameter φ^k is the elasticity of substitution between conventional money and CBDC. Equation (7) reveals that high- and low-income households may differ with respect to their preferred mix of money holdings. Our model thus reflects that high-income households may have a more pronounced willingness to use CBDC than low-income households, as pointed out, for example, by Li (2022).

A household's overall demand for money m_t^k will always be satisfied, i.e., overall money supply always adjusts to the overall demand. However, the central bank may limit the amount of CBDC each household is allowed to hold, i.e.,

$$0 \leq m_{CB,t}^k \leq m_{CB,t}^{max}. \tag{8}$$

If the constraint on CBDC holdings is binding, the adjustment will thus work via the supply of conventional money,[3] and the composition of overall real money holdings will deviate from the household's preferred mix. A household's actual mix of money holdings Γ_t^k is thus given by[4]

$$\Gamma_t^k = \frac{m_{C,t}^k}{m_{C,t}^k + m_{CB,t}^k} = \begin{cases} \Gamma_t^{uncon,k} = \frac{m_{C,t}^k}{m_{C,t}^k + m_{CB,t}^{uncon,k}} & \text{if} \quad m_{CB,t}^k \leq m_{CB,t}^{max}, \\ \Gamma_t^{con,k} = \frac{m_{C,t}^k}{m_{C,t}^k + m_{CB,t}^{max}} & \text{if} \quad m_{CB,t}^k > m_{CB,t}^{max}. \end{cases} \tag{9}$$

with $\Gamma_t^{con,k}$ being the mix of money holdings if the constraint is binding and $\Gamma_t^{uncon,k}$ if it is not binding. If the constraint on CBDC holdings is binding, the respective household will incur additional costs. We denote these costs as transaction costs, with $\zeta_t^k - 1$ denoting the transaction costs per unit of consumption. They are reflected by

$$\zeta_t^k = 1 + \left(\Gamma_t^k - \Gamma_t^{uncon,k}\right)^2. \tag{10}$$

If the preferred mix of money holdings $\Gamma_t^{uncon,k}$ cannot be realized, $\zeta_t^k > 1$, i.e., household k will face transaction costs. This implies an increase in overall consumption expenditures $P_t \zeta_t^k C_t^k$. Another interpretation is that transaction costs reduce the amount of transactions for a given amount of expenditures. Thus, they can also be viewed as the transactions not undertaken by a household due to the unavailability of the preferred payment option.

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[3] Note that if a central bank does not provide CBDC, $m_{CB,t}^{max} = 0$ and $m_t^k = m_{C,t}^k$ will hold.

[4] A somewhat related approach can be found in Ferrari Minesso et al. (2022). They include a preferred mix of payment instruments in the utility function, thereby capturing preferences of households with respect to conventional money and CBDC. We deviate from this approach by specifically considering that CBDCs might facilitate transactions, i.e., that the availability of CBDCs might reduce transaction costs.

Note that transaction costs increase disproportionately in the deviation of the actual mix of money holdings from the preferred mix.

The first order conditions (FOCs) for a household's optimal mix of money holdings are

$$(\omega^k)^{\frac{1}{\varphi^k}} \left(m^k_{C,t}\right)^{-\frac{1}{\varphi^k}} \leq (1-\omega^k)^{\frac{1}{\varphi^k}} \left(m^k_{CB,t}\right)^{-\frac{1}{\varphi^k}}, \tag{11}$$

$$\left[(1-\omega^k)^{\frac{1}{\varphi^k}} \left(m^k_{CB,t}\right)^{-\frac{1}{\varphi^k}} - (\omega^k)^{\frac{1}{\varphi^k}} \left(m^k_{C,t}\right)^{-\frac{1}{\varphi^k}}\right] \left[m^{max}_{CB,t} - m^k_{CB,t}\right] = 0, \tag{12}$$

and

$$m^{max}_{CB,t} - m^k_{CB,t} \geq 0. \tag{13}$$

The FOCs reveal that if the constraint the central bank imposes on a household's CBDC holdings is not binding, its marginal benefits of conventional money holdings (LHS of (11)) will equal those from CBDC holdings (RHS of (11)). However, if the constraint is binding, the household's marginal benefits of CBDC holdings will be higher than those from holding conventional money, but balancing marginal benefits is not possible and the household will hold the maximum amount the central bank sets.[5]

Furthermore, each household has to decide on its optimal amount of labor and its optimal consumption path over time. Defining the marginal utility of consumption as $U^k_{c,t} \equiv \left(\frac{Z_t}{C^k_t - \Psi^k C^k_{t-1}} - \frac{\mathbb{E}_t[Z_{t+1}]\Psi^k \beta}{\mathbb{E}_t\left[C^k_{t+1}\right] - \Psi^k C^k_t}\right)$, the respective optimality conditions are

$$\chi^k N^{k^{\eta^k}}_t = U^k_{c,t} \frac{W^k_t}{P_t} \Phi^k_t, \tag{14}$$

$$U^k_{c,t} = \beta(1+i_t)\, \mathbb{E}_t \left[U^k_{c,t+1} \frac{P_t}{P_{t+1}} \frac{\Phi^k_{t+1}}{\Phi^k_t}\right], \tag{15}$$

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[5] Formally, if the constraint is not binding, the first square bracket term in (12) equals zero, the second may be greater than zero. If the constraint is binding, the first square bracket term in (12) is greater than zero so that the second must be zero.

with

$$\Phi_t^k \equiv \frac{1}{\zeta_t^k} - \frac{\zeta_{m_{C,t}}^k C_t^k}{m_{m_{C,t}}^k \zeta_t^k}, \tag{16}$$

where $\zeta_{m_{C,t}}^k$ denotes marginal transaction costs with respect to conventional money holdings, and $m_{m_{C,t}}^k$ is marginal demand for money with respect to conventional money holdings given by

$$\zeta_{m_{C,t}}^k = 2(\Gamma_t^k - \Gamma_t^{uncon,k}) \frac{m_{CB,t}^k}{(m_{C,t}^k + m_{CB,t}^k)^2}, \tag{17}$$

$$m_{m_{C,t}}^k = \left(m_t^k\right)^{\frac{1}{\varphi^k}} (\omega^k)^{\frac{1}{\varphi^k}} \left(m_{C,t}^k\right)^{-\frac{1}{\varphi^k}}.$$

If the constraint on CBDC holdings is not binding, no transaction costs will be incurred, $\zeta_t^k = \Phi_t^k = 1$, since $\zeta_{m_{C,t}}^k = 0$ as shown by equation (17). Intuitively, if households can hold as much CBDC as they wish, no transaction costs will be incurred, and equations (14) and (15) then represent the standard FOCs for a household's optimal amount of labor and consumption path. The LHS of (14) represents marginal disutility of work, the RHS marginal utility. The latter arises from the additional possible consumption when working one more hour. Equation (15) represents the Euler equation: If the household has no time preference ($\beta = 1$), there are no interest payments ($i_t = 0$) and no inflation ($P_t = P_{t+1}$), (15) decreases to $U_{c,t}^k = \mathbb{E}_t[U_{c,t+1}^k]$, i.e., it will be optimal to consume the same quantity in each period (consumption smoothing). This will be "disturbed" if households have a time preference, receive interest payments on their savings and/or if they expect price changes.

If the constraint on CBDC holdings is binding, transaction costs will be incurred ($\zeta_t^k > 1$ and $\Phi_t^k < 1$) and the optimal behavior of the household changes. The marginal utility of work decreases as part of the wage cannot be used any longer to pay for beneficial consumption but for transaction costs. The variable Φ_t^k, or more precisely $(1 - \Phi_t^k)$, thus reflects how much the household's marginal utility of work decreases due to transaction costs, i.e., due to the imposed constraint on CBDC holdings. Obviously, as shown in (16), this decrease will be more pronounced the more the household's actual mix of money holdings deviates from its preferred mix (i.e., the more important CBDC holdings are for this household). Consequently, the lower the Φ_t^k, the more the household suffers from the imposed restriction. Equation (15) shows that the constraint may also be a "disturbance factor" to consumption smoothing. If a household expects its future marginal utility of work to be lower than today ($\Phi_{t+1}^k < \Phi_t^k$), optimality requires it to work and consume more in period t than in $t+1$.[6]

The shared bond market implies risk sharing in the form of

$$U_{c,t}^k = \phi_t^k (U_{c,t}^{-k}) \frac{\Phi_t^{-k}}{\Phi_t^k}, \tag{18}$$

with $\phi_t^k \equiv \frac{U_{c,SS}^k}{U_{c,SS}^{-k}} \frac{\Phi_{SS}^k}{\Phi_{SS}^{-k}}$, where SS denotes the zero inflation steady state and $U_{c,SS}^k = \frac{1-\Psi^k \beta}{(1-\Psi^k) C_{SS}^k}$.

2.2 Firms

There is a continuum of firms indexed by $j \in [0,1]$ using identical technology. Each firm produces a differentiated good and supplies it on a monopolistically competitive market. We assume price rigidities à la Calvo (1983), assuming that only a fraction $1-\Lambda$ of firms is able to adjust their prices in each period. The CES production function of the firm is given by

$$Y_{j,t} = \left(\alpha N_{j,t}^{H\,\frac{\varphi^N - 1}{\varphi^N}} + (1-\alpha) N_{j,t}^{L\,\frac{\varphi^N - 1}{\varphi^N}} \right)^{\frac{\varphi^N}{\varphi^N - 1}}, \tag{19}$$

with $\alpha > (1-\alpha)$ and φ^N being defined as the elasticity of substitution between labor from households H and L.

Firm j's real total costs are given by

$$TC_{j,t} = A_t \left(w_t^H N_{j,t}^H + w_t^L N_{j,t}^L \right), \tag{20}$$

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[6] Assume again that $\beta = 1$, $i_t = 0$, and $P_t = P_{t+1}$. Then ($\Phi_{t+1}^k < \Phi_t^k$) requires $U_{c,t+1}^k > U_{c,t}^k$ and thus $C_{t+1}^k < C_{c,t}^k$ to fulfil the FOC given by (15).

with w_t^k being defined as the real wage. A_t is an AR(1) cost-push shock. Cost minimization for a given level of output requires

$$\frac{\alpha}{1-\alpha}\left(\frac{N_{j,t}^H}{N_{j,t}^L}\right)^{-\frac{1}{\varphi^N}} = \frac{w_t^H}{w_t^L}. \tag{21}$$

By choosing $P_{j,t}$, firms maximize their expected discounted stream of real profits given by

$$\mathbb{E}_t\left[\sum_{\iota=0}^{\infty}\beta^\iota\Lambda^\iota\Omega_{t,t+\iota}\left(\frac{P_{j,t}}{P_{t+\iota}}Y_{j,t+\iota|t} - TC\left(Y_{j,t+\iota|t}\right)\right)\right], \tag{22}$$

subject to

$$Y_{j,t+\iota|t} = \left(\frac{P_{j,t}}{P_{t+\iota}}\right)^{-\theta} Y_{t+\iota}, \tag{23}$$

where $\beta^\iota\Omega_{t,t+\iota}$ is the stochastic discount factor, with $\Omega_{t,t+\iota} \equiv \frac{\kappa U_{c,t+\iota}^H + (1-\kappa)U_{c,t+\iota}^L}{\kappa U_{c,t}^H + (1-\kappa)U_{c,t}^L}$. $Y_{j,t+\iota|t}$ denotes the output in period $t+\iota$ for a firm that is able to adjust its price in the present period and $Y_{t+\iota}$ denotes the economy-wide output. Marginal costs can be determined as

$$mc_t = \frac{A_t\left(w_t^H + w_t^L\left(\frac{1-\alpha}{\alpha}\frac{w_t^H}{w_t^L}\right)^{\varphi^N}\right)}{\left(\alpha + (1-\alpha)\left(\frac{1-\alpha}{\alpha}\frac{w_t^H}{w_t^L}\right)^{\varphi^N-1}\right)^{\frac{\varphi^N}{\varphi^N-1}}}. \tag{24}$$

Note that we drop index j as marginal costs are independent of the individual level of output. Then, the optimal price is given by

$$p_t^* = \mu\frac{x_{1,t}}{x_{2,t}}, \tag{25}$$

where $p_t^* \equiv \frac{P_t^*}{P_t}$, $\mu \equiv \frac{\theta}{\theta-1}$, and the auxiliary variables are defined as

$$x_{1,t} \equiv U_{c,t}Y_t mc_t + \Lambda\beta\,\mathbb{E}_t\left[\Pi_{t+1}^{\theta}x_{1,t+1}\right], \tag{26}$$

$$x_{2,t} \equiv U_{c,t}Y_t + \Lambda\beta\,\mathbb{E}_t\left[\Pi_{t+1}^{\theta-1}x_{2,t+1}\right], \tag{27}$$

where $U_{c,t} \equiv \kappa U^H_{c,t} + (1-\kappa)U^L_{c,t}$ and $\Pi_t \equiv \frac{P_t}{P_{t-1}}$. Equations (25), (26), and (27) are the standard conditions for optimal price setting behavior in New Keynesian models, relating the price to current and future marginal costs and the development of the price level.

2.3 Central Bank

The central bank sets the nominal interest rate and supplies money. It sets the nominal interest rate according to a Taylor rule given by

$$i_t = \rho + \phi_{\pi,i}\pi_t, \tag{28}$$

with $\rho \equiv log\left(\frac{1}{\beta}\right)$ and $\pi_t \equiv log(\Pi_t)$. The parameter $\phi_{\pi,i} > 1$ determines the strength of the central bank's reaction to changes in inflation.

The central bank's total money supply is denoted by m^S_t. The central bank adjusts m^S_t to the households' total demand for money. Their total demand is always satisfied, but potentially not in the preferred composition, as the central bank can set a maximum amount of CBDC holdings, $m^{max}_{CB,t}$, each household is allowed to hold. Naturally, the no-CBDC regime implies $m^{max}_{CB,t} = 0 \forall t$. Conversely, the unconstrained regime implies that the central bank always satisfies CBDC demand. The central bank's behavior with respect to this constraint is therefore only relevant in the constrained regime and the MP regime. It is captured by

$$log(m^{max}_{CB,t}) = log(m^{max}_{CB,SS}) - \phi_{\pi,m} log(\pi_t), \tag{29}$$

where $m^{max}_{CB,SS}$ is the maximum amount of CBDC holdings in the steady state, and $\phi_{\pi,m}$ is the reaction coefficient of the central bank to inflation. In the constrained CBDC regime, $\phi_{\pi,m} = 0$, i.e., the amount of CBDC each household is allowed to hold is exogenously set by the central bank. In the MP regime, $\phi_{\pi,m} > 0$, i.e., the central bank adjusts the CBDC limit according to the inflation development in the economy. For instance, when the central bank observes inflation, it decreases the quantity of CBDC that households are allowed to hold. This implies that households whose preferred CBDC holdings exceed the limit set by the central bank incur higher transaction costs, consumption decreases, which implies a dampening effect on inflation (vice versa for low inflation).

2.4 Equilibrium

The goods market clears

$$Y_t = \kappa \zeta_t^H C_t^H + (1-\kappa)\zeta_t^L C_t^L, \tag{30}$$

i.e., overall production covers consumption demand and transaction costs. Labor market clearing implies

$$\int_0^1 N_{j,t}^k dj = N_t^k. \tag{31}$$

Bonds are in zero net supply

$$B_t^k + B_t^{-k} = 0. \tag{32}$$

The money market clears

$$m_t^S = m_t^k. \tag{33}$$

In particular, demand for conventional money is always satisfied:

$$m_{C,t}^S = m_{C,t}^k. \tag{34}$$

Concerning CBDC, we have to distinguish between two cases: if demand for CBDC exceeds supply, the central bank determines the amount of CBDC held by the households. If demand is lower than supply, each household determines its CBDC holdings:

$$m_{CB,t}^S = m_{CB,t}^k. \tag{35}$$

3 Model Analysis

3.1 Calibration

Table 1 depicts the model calibration. We follow Ferrari Minesso et al. (2022) by setting the elasticity of substitution between good varieties to 6, the elasticity of substitution between conventional money and CBDC to 0.5,[7] and the weight on conventional money of high income households to 0.5 (implying an equal weight on CBDC). In order to include the fact that households with lower income have a lower preference for CBDC (see Introduction), we set the weight on conventional money by household L to 0.8. We further set the habit parameter and the inverse Frisch elasticity of labor supply to values that are realistic for European countries (see Albonico et al., 2019).

Table 1: Calibration.

	Description	Value	Target/Source
		Households	
κ	Share of H-households	0.5	Equal share of H- and L-households
Ψ_k	Habit parameter	0.8	Albonico et al. (2019)
χ	Scaling parameter labor	1	Galí (2015)
η_k	Inverse Frisch elasticity	2	Albonico et al. (2019)
θ	Elasticity of substitution between varieties	6	Ferrari Minesso et al. (2022)
β	Discount factor	0.99	Annual interest rate: 4%
ω_H	Weight on conventional money H	0.5	Ferrari Minesso et al. (2022)
ω_L	Weight on conventional money L	0.8	Greater preference for conventional money
φ_k	Elasticity of substitution between conventional money and CBDC	0.5	Ferrari Minesso et al. (2022)
		Firms	
α	Productivity household H	2/3	Higher productivity of H
φ_N	Elasticity of substitution between labor of H and L	2	Acemoglu (2002)
Λ	Price stickiness parameter	0.75	Average price duration: 4 quarters
		Central Bank	
$\phi_{\pi,i}$	Taylor rule coefficient: interest rate	1.5	Galí (2015)
$\phi_{\pi,m}$	Taylor rule coefficient: CBDC	5	Analysis Parameter

Moreover, we assume that household H is more productive (implying higher income) and set the elasticity of substitution between labor from households H and L to 2, thereby

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[7] Assenmacher et al. (2021) use the same value for the elasticity of substitution between deposits and CBDC relating to a firm's decision on how to finance capital purchases.

following Acemoglu (2002), who presents this value for the elasticity of substitution between skilled and unskilled labor.

Finally, standard parameters such as the scaling parameter on labor, the discount factor, the level of price stickiness, and the Taylor rule coefficient of inflation are chosen as in Galí (2015).

3.2 Steady-State Analysis

We compare the steady state values of the model under the no-CBDC regime, the unconstrained regime, and the constrained regime.[8] Comparing the no-CBDC regime with the unconstrained regime first, Table 2 reveals that the introduction of a CBDC increases the utility of both households. Both consume more without working more. As both can realize their preferred mix of money holdings, no transaction costs arise. This means that no output has to be used to cover transaction costs, but total output can be consumed.[9] Due to its higher preference for using CBDC, household H benefits more from its introduction. Household H's larger preference for using CBDC is also reflected by the relatively larger decrease in its conventional money holdings after if it becomes possible to use CBDC.

However, the introduction of a CBDC in a way that households are allowed to hold as much CBDC as they wish, is not under consideration by central banks as this may cause severe problems for the banking sector because banks may lose parts of their deposits (Adalid et al., 2022; Panetta, 2022). Therefore, we proceed by analyzing the more realistic constrained regime, in which the amount of CBDC each household is allowed to hold is limited. We assume that this constraint is only binding for household H.[10]

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[8] The MP regime coincides with the constrained regime in steady state, as the reaction of the central bank is only relevant after shocks.

[9] Note that only the consumption-relevant output increases, but total output does not change, as labor input does not change: Despite the higher consumption per hour of work, households have no incentive to work more. To clarify this, we assume a representative household so that we can skip the index k and $C\zeta = Y$. Furthermore, we neglect habit formation so that $\psi = 0$, and consider that $U_{c,ss} = \frac{1}{C}$. Then, in steady state, (14) reduces to $\chi N^{\eta} = \frac{W}{P}\frac{1}{C\zeta}\left(1 - \frac{\zeta_{m_C} C}{m_{m_C}}\right) = \frac{W}{P}\frac{1}{Y}\left(1 - \frac{\zeta_{m_C} C}{m_{m_C}}\right)$, and in the no-CBDC regime as well as in the unconstrained regime in particular to $\chi N^{\eta} = \frac{W}{P}\frac{1}{C\zeta} = \frac{W}{P}\frac{1}{Y}$. The introduction of CBDC in an unconstrained manner reduces ζ equal to one. However, as Y does not change (it would only change if the household worked more or less), the share of the output which is no longer used for covering transaction costs must be consumed. If the household worked more, marginal disutility of work (LHS of the latter equation) would increase. However, then also more output would be produced leading to higher consumption, implying a decrease in marginal utility of work (RHS). Marginal disutility and marginal utility of work would diverge. The introduction of CBDC in an unconstrained manner thus leads to higher consumption per each working hour, but marginal utility of work does not increase so that labor input L and thus overall output Y do not change.

[10] The qualitative results of our analysis would not change if both households were affected by the constraint.

Table 2: Steady State Comparison.

Variable	Description	Relative Steady State Value No CBDC	CBDC constr.	CBDC unconstr.
C_{SS}^{L}	Consumption L	1	0.99	1.04
C_{SS}^{H}	Consumption H	1	1.07	1.25
$Y_{C,SS}$	Consumption-Relevant Output	1	1.03	1.15
Y_{SS}	Output	1	0.92	1
N_{SS}^{L}	Labor L	1	1	1
N_{SS}^{H}	Labor H	1	0.88	1
$m_{C,SS}^{L}$	Conventional Money Holdings L	1	0.76	0.80
$m_{C,SS}^{H}$	Conventional Money Holdings H	1	0.83	0.50
$m_{CB,SS}^{L}$	CBDC Holdings L	–	1	1.05
$m_{CB,SS}^{H}$	CBDC Holdings H	–	1	1.61
U_{SS}^{L}	Utility L	1	0.998	1.005
U_{SS}^{H}	Utility H	1	1.015	1.03

Notes. All values relative to the case without CBDC. Exception: CBDC holdings, which are displayed relative to the case where a CBDC constraint imposed by the central bank. $Y_{C,SS} \equiv (1-\kappa)C_{SS}^{L} + \kappa C_{SS}^{H}$.

Table 2 reveals that also in this constrained regime, the introduction of CBDC implies a higher utility for the constrained household H. The household consumes more and works less. The possibility to use CBDC as a means of payment, even in a constrained manner, implies an increase in consumption as less of the total output has to be used for covering transaction costs. However, transaction costs are still incurred ($\zeta_t^H > 1$), so that the increase in consumption after the introduction of a CBDC is lower than in the unconstrained regime. However, in the constrained regime, the constrained household H can affect the transaction costs per unit of consumption ($\zeta_t^H - 1$) via its consumption choice. The variable ζ_t^H is no longer constant.[11] Due to this possibility, the household actually works less compared to the other regimes. To clarify on this, we compare the constrained regime with the unconstrained regime. In the former, the household consumes less. If the household consumes less, less money will be needed. However, due to the binding constraint on CBDC holdings, the household reduces only its conventional money holdings, so that its share in total money holding decreases. This implies that the money mix held by household H moves closer to its preferred mix of money holdings which reduces the transaction costs per unit of consumption ($\zeta_t^H - 1$). By working less, less

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[11] In the unconstrained regime $\zeta_t^k = 1$, in the no-CBDC regime $\zeta_t^k > 1$ but constant as the share of conventional money holdings in total money holdings is obviously always one (see equations (9) and (10)).

output is produced, but a higher share of total output can be used for consumption as fewer transaction costs are incurred.[12]

Note that the reduced labor supply by household H implies that its marginal productivity increases so that the relative marginal productivity of household L decreases. Consequently, L's real wage decreases. If the effect of this decrease outweighs the effect of lower transaction costs on its marginal utility of labor, the introduction of a CBDC will even lead to lower consumption and thus, lower utility of household L.[13] Obviously, the real-wage effect will be higher the more restrictive the CBDC holdings are, i.e., the lower the maximum amount of CBDC is that each household is allowed to hold. The calibration used in this paper implies that the real-wage effect outweighs the transaction cost effect. Household L's consumption is partly crowded out by household H's consumption. Consequently, the introduction of CBDC implies redistributional effects in this case. However, also in a constrained manner, the introduction of a CBDC implies an increase in economy-wide output, consumption and thus utility.

3.3 Dynamic Analysis

3.3.1 Demand Shock

Figure 1 shows the impulse responses of the model to a negative 1% demand shock that affects both households symmetrically. The impulse responses are shown for the four different CBDC regimes. In all regimes, the shock implies that households consume less and thus hold less money. Firms produce less and hire less labor. Inflation decreases and the central bank reacts by decreasing the nominal interest rate to incentivize consumption and mitigate the effects of the shock.

Analyzing the differences in the impulse responses of the different CBDC regimes, we start with the comparison of the no-CBDC and the unconstrained regime. In both regimes, the impulse response functions of all variables coincide, except for CBDC holdings. The reason is that in both regimes transaction costs per unit of consumption are constant (see

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[12] Formally, this is shown by the reduced form of equation (14) (general form) given in footnote 9. If the household works less, its marginal disutility of work (LHS) will decrease. The resulting lower output Y leads to an increase in marginal utility of work (RHS), but this will be overcompensated by the higher share of consumption in total output C/Y. Due to the reduced share of conventional money in total money holdings, the mix of money holdings comes closer to its optimum in the unconstrained regime, i.e., fewer transaction costs are incurred.

[13] Obviously, household L's decrease in consumption and real wage have an impact on its labor supply. However, these effects work in the opposite direction and the net effect (here, an increase in labor supply) is so small that it is not visible in the results given in Table 2.

footnote 11). Naturally, in the unconstrained regime CBDC holdings decrease proportionally to overall and conventional money holdings.

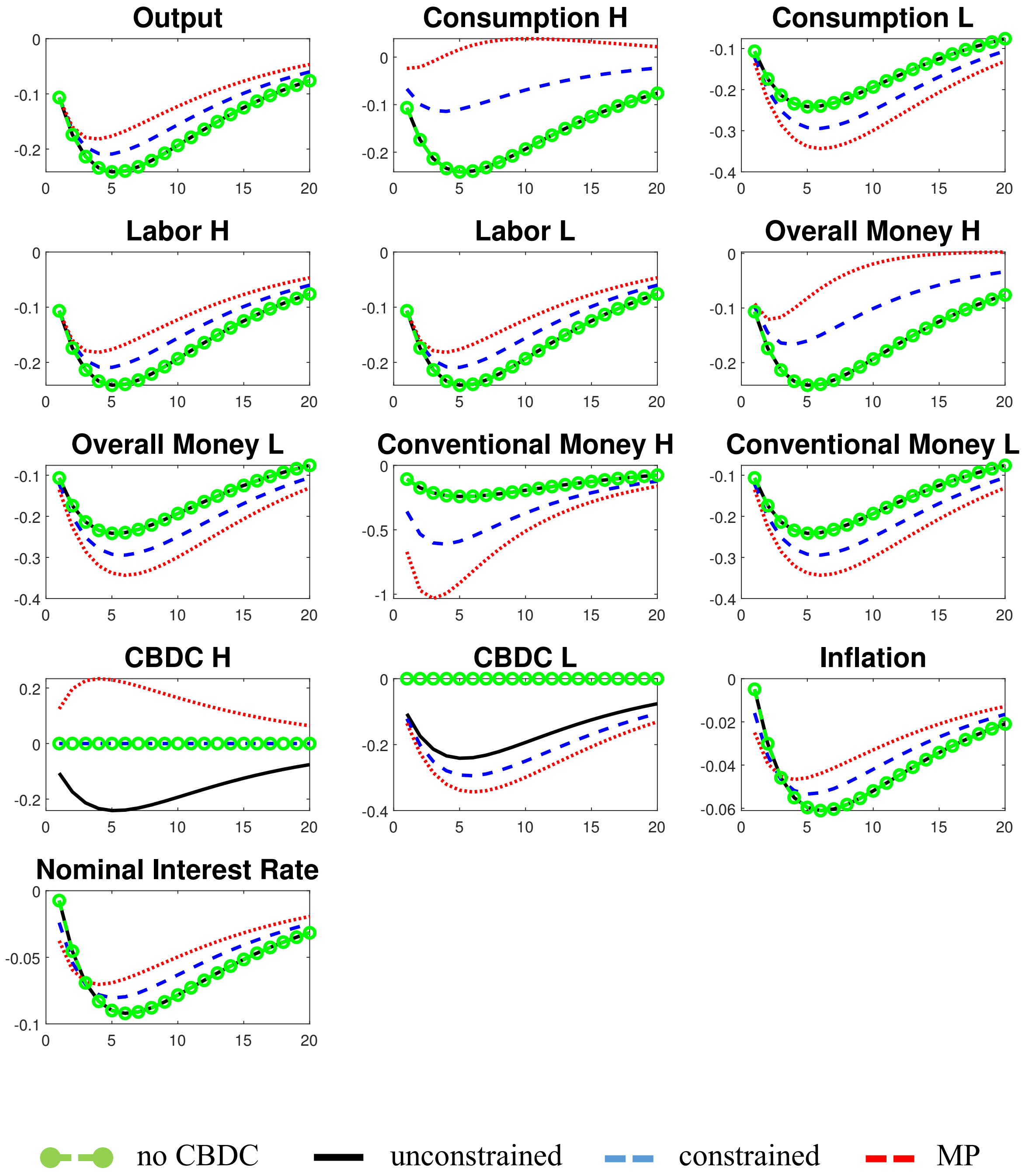

Figure 1: Impulse Responses to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$.

We proceed with comparing the impulse responses of the no-CBDC/unconstrained regime with the ones of the regimes with a CBDC limit (constrained and MP regime). In the constrained/MP regime, the constraint is not binding for household L but is for household H. As a result, the optimal amount of CBDC is held by household L but not by household H. However, CBDC still implies lower deviations of output and inflation from their steady states due to the facilitation of transactions (i.e., a decrease in transaction costs per unit of consumption) in comparison to the no-CBDC/unconstrained regime. The negative demand shock leads household H to reduce its conventional money holdings but not its CBDC holdings as the constraint is still binding. This implies a decrease in transaction costs per unit of consumption, which is the main difference between the constrained/MP regime and the no-CBDC/unconstrained regime, where transaction costs per unit of consumption are constant. In the constrained/MP regime, household H experiences a less pronounced decrease in consumption due to the decrease in transaction costs per unit of consumption. Consequently, output and thereby labor and inflation decrease less in this case. However, this occurs at the expense of the consumption of household L: a relatively higher consumption of household H, ceteris paribus, leads to higher prices and a decrease in demand for goods by household L. Overall, the shock absorption capabilities of the economy are strengthened by the constrained/MP regime through the stabilization of household H's consumption, while household L's consumption decreases even further.

Upon comparing the constrained regime with the MP regime, we find that these effects are even more pronounced in the MP regime. In response to a negative demand shock, the central bank loosens the constraint by increasing the maximum amount of CBDC per household, causing household H's real CBDC holdings to increase and its real conventional money holdings to decrease even more. Transaction costs per unit of consumption decrease as household H is closer to its optimal mix of money holdings. Household H reduces its consumption less and aggregate output decreases less. However, household L's consumption decreases even more strongly. Overall, output and inflation can be stabilized and decrease less compared to the case where CBDC is not used as a monetary policy instrument. However, the use of the CBDC limit as a monetary policy instrument has redistributional effects.

3.3.2 Cost-Push Shock

Figure 2 shows the impulse responses of the model to a 1% cost-push shock for the four CBDC regimes.

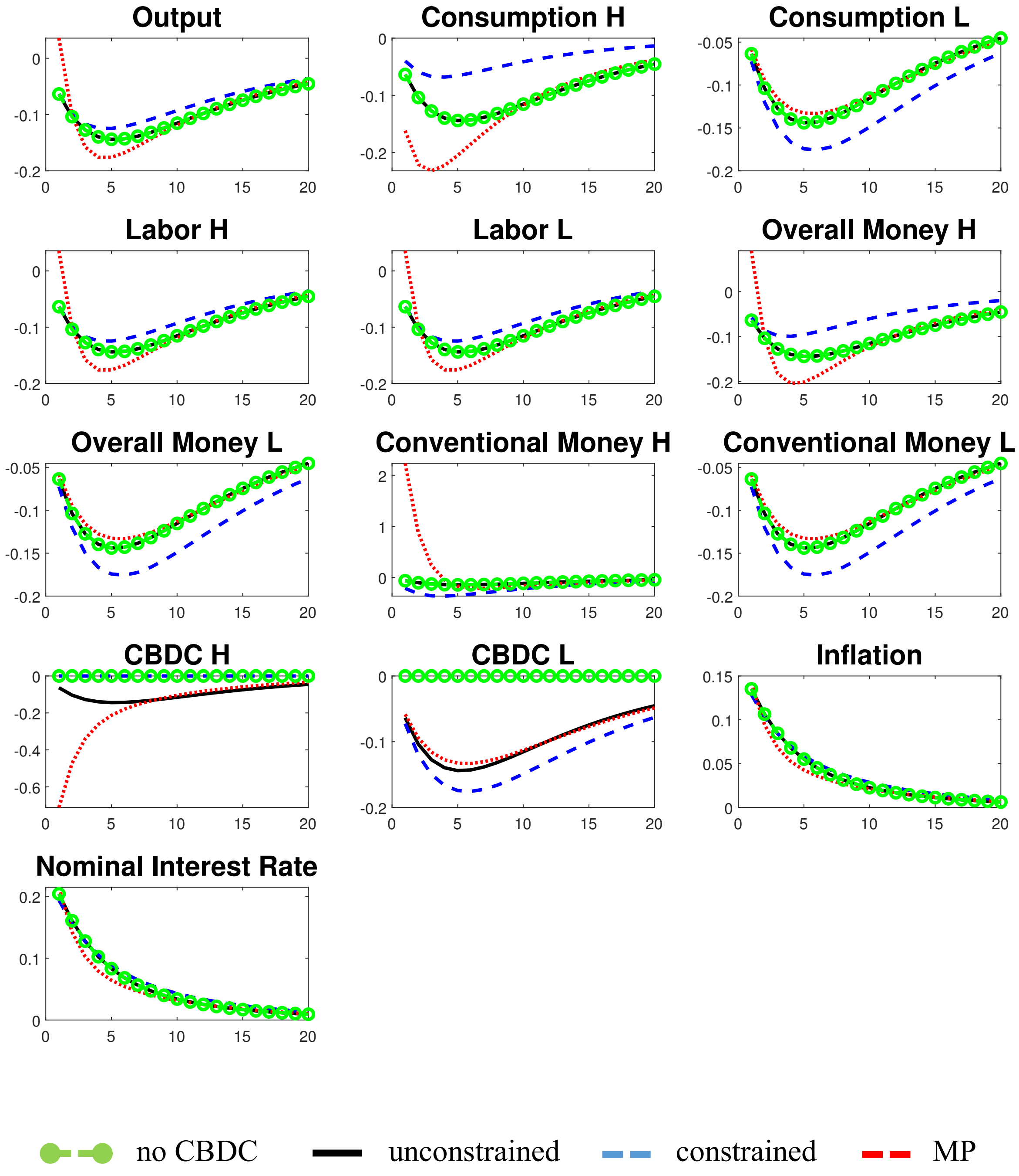

Figure 2: Impulse Responses to a 1% Cost-Push Shock (A^k) with Persistence $\rho_A = 0.9$.

In all cases, the increase in costs for firms leads to an increase in prices, implying a decrease in consumption and thus money holdings. Firms hire less labor and produce less. The central bank reacts to the increase in inflation by increasing the nominal interest rate. As in the case of a demand shock, the impulse responses of all model variables coincide for the no-CBDC and the unconstrained regime (except for CBDC holdings).

Upon comparing the impulse responses of the constrained/MP regime with the ones of the unconstrained/no-CBDC regime, we find that consumption of household H decreases less in the constrained/MP regime. This is due to lower transaction costs per unit of consumption: the decrease in consumption implies lower conventional money demand of household H but a constant demand for CBDC as the constraint is binding. This leads to lower transaction costs per unit of consumption for H, as H is closer to its preferred money mix, implying a lower decrease in consumption. Consequently, output decreases less and prices increase even more. This leads household L to reduce its consumption even more in the constrained/MP regime.

In the MP regime, the central bank is able to stabilize inflation by adjusting the CBDC limit. It reacts to the increase in inflation by decreasing the maximum amount of CBDC to further reduce consumption. The constraint thus becomes more restrictive but only for household H. Household H therefore holds even less CBDC than it wishes to hold and increases its conventional money holdings in return. Transaction costs per unit of consumption increase. As a result, household H's consumption decreases more than in the other three regimes, while household L's consumption decreases less. Overall, inflation increases less than in the other regimes. However, output decreases even more as the central bank reduces the amount of CBDC (and therefore negatively affects consumption). Monetary policy thus has a stronger impact on inflation and the effects of monetary policy are amplified. However, this also amplifies the negative effects on output. In addition, using CBDC as a monetary policy instrument implies redistributional effects.

4 Conclusion

Over the past years, there has been an ongoing debate about advantages and disadvantages of introducing a CBDC, including if and how central banks should issue it. In particular, households differ in their preferences for CBDC depending on their income. Against this background, we investigate the macroeconomic effects of a CBDC in an economy with a heterogeneous household sector.

Our paper develops a New Keynesian model in which households differ in their preferences to hold CBDC. We consider a high- and a low-income household, with the high-income household preferring to hold a larger amount of CBDC than the low-income household. We analyze the macroeconomic consequences of four different CBDC regimes. In the first, no CBDC exists. In the second, access to CBDC for each household is unconstrained. In the third, the central bank sets a maximum amount of CBDC each household is allowed to hold. In the fourth, in addition, the central bank uses this maximum amount of CBDC each household is allowed to hold as a monetary policy instrument, i.e., the central bank changes the maximum amount of CBDC to potentially stabilize prices after adverse shocks.

We find that the introduction of a CBDC leads to a higher economy-wide utility in steady state. Moreover, the shock absorption capability increases in an economy with CBDC. After a negative demand shock, the central bank can stabilize prices and output more effectively. This particularly applies to the fourth CBDC regime where the central bank can increase the maximum amount of CBDC each household is allowed to hold after the demand shock. After a cost-push shock, the utilization of the CBDC limit as a monetary policy instrument also increases shock absorption capabilities as monetary policy has a stronger impact on inflation. However, the use of a CBDC as a monetary policy instrument also amplifies the negative effects on output. Generally, the introduction and existence as well as the utilization of a CBDC as a monetary policy instrument implies distributional effects across households.

Our findings raise questions for future research with respect to the use of a CBDC limit as a monetary policy instrument, as monetary policy can be conducted more effectively on the one hand, but distributional effects are involved on the other. An investigation into the effects of other CBDC regimes in an economy with a heterogeneous household sector seems interesting for future research.

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