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Conference Paper

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Beiträge zur Jahrestagung des Vereins für Socialpolitik 2023: Growth and the "sociale Frage"

Provided in Cooperation with:

Verein für Socialpolitik / German Economic Association

Suggested Citation: Magin, Jana; Neyer, Ulrike; Stempel, Daniel (2023) : The Macroeconomic Effects of Different CBDC Regimes in an Economy with a Heterogeneous Household Sector, Beiträge zur Jahrestagung des Vereins für Socialpolitik 2023: Growth and the "sociale Frage", ZBW - Leibniz Information Centre for Economics, Kiel, Hamburg

This Version is available at:

<https://hdl.handle.net/10419/277656>

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

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August 2023

Abstract

Many central banks discuss the introduction of a Central Bank Digital Currency (CBDC). Empirical evidence suggests that households differ in their demand for a CBDC. 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 facilitates transactions. 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 depending on the state of the economy. Generally, we find that the introduction of a CBDC increases economy-wide utility as it allows for higher consumption. Moreover, if a binding limit on CBDC-holdings is introduced, the shock absorption capability of the economy will increase. Furthermore, if this limit is used as a monetary policy instrument, prices will be stabilized more effectively after adverse shocks. However, the introduction of a CBDC implies distributional effects across households.

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

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

*We are grateful to Michael C. Burda, Katharina Erhardt, Alex Grimaud, Frank Heinemann, Christian R. Proaño, Peter Tillmann, Dominique Torre, and Leopold Zessner-Spitzenberg for their valuable comments and suggestions. We thank participants of the International Symposium on Money, Banking and Finance, the FIW Research Conference, the Annual Central Bank Macroeconomic Modelling Workshop, the BETA Workshop on DSGE Models, and the IMK Workshop, as well as seminar participants at Heinrich Heine University Düsseldorf and the MAGKS Colloquium for their helpful remarks and comments.

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1 Introduction

Central banks worldwide consider and debate the introduction of a Central Bank Digital Currency (CBDC). 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. The introduction of a Retail CBDC would therefore allow central banks to provide the broader public with a digital form of central bank money. So far, the broader public can only use cash to pay with public, i.e., central bank money. However, due to a changed shopping and payment behavior, the use of cash is declining as people prefer to pay digitally (Deutsche Bundesbank, 2021a; European Central Bank, 2022). Consequently, there is an increasing demand for a secure, efficient, and digital means of payment, which is the main reason for considering the introduction of a CBDC (European Central Bank, 2023a).¹ In this context, Bordo and Levin (2017) emphasize that the introduction of a CBDC would facilitate transactions. Currently, most major central banks consider such an introduction. For instance, the European Central Bank (ECB) discusses the introduction of a digital euro as an additional means of payment in the euro area besides conventional forms such as cash and deposits. However, if the digital euro is introduced, its holdings will most likely be limited (Panetta, 2022). One of the reasons to consider a limit is to address concerns of bank disintermediation and a potential decline in bank profitability (Adalid et al., 2022; Burlon et al., 2022; Bellia and Calès, 2023; Muñoz and Soons, 2023). Studies identify a demand for a CBDC (Bijlsma et al., 2021; Deutsche Bundesbank, 2021b). However, households differ in the extent to which they want to hold CBDC (Li, 2022). In particular, households with relatively low income tend to have a higher preference for cash and a lower preference for digital payment options. For households with relatively high income the opposite can be observed. This implies that the impact of an introduction of a CBDC might differ across households.

Against this background, this paper investigates the macroeconomic effects 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

¹For 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). For the progress on a digital euro see European Central Bank (2023b) and Proposal for a Regulation of the European Parliament and of the Council on the establishment of the digital euro COM/2023/369 final.

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”), thereby capturing the proposed implementation of a limit on CBDC holdings by the ECB, for instance. In the fourth regime, the central bank can use the CBDC limit as a monetary policy instrument (“monetary policy regime”). Furthermore, we capture the facilitation of transactions by a CBDC by introducing transaction costs into our model. If households are not able to hold as much CBDC as they want to hold, i.e., if their actual mix of conventional forms of money (cash and bank deposits) and CBDC deviates from their optimal, preferred mix, they will face transaction costs. They cannot use part of their income for consumption but they have to use it to cover these costs. For example, households have to replace online purchases by an in-store alternative, which implies a sort of shoe-leather costs.

The main results of this paper are: (i) The introduction of a CBDC leads to higher economy-wide utility. (ii) Setting a binding maximum amount of CBDC each household is allowed to hold improves the shock absorption capability of the economy. (iii) Using CBDC as a monetary policy instrument allows to stabilize prices more effectively. (iv) The introduction of a CBDC in a constrained manner and its use as a monetary policy instrument implies distributional effects across households.

The main driver for these results are the transaction costs households will face if they cannot hold their preferred mix of means of payments. An existing demand for CBDC therefore implies decreasing transaction costs, and thereby an increasing utility, if a CBDC is introduced. Changing transaction costs per unit of consumption are the reason for the improved shock absorption capability under the regimes with binding CBDC constraints. Contrary to the no-CBDC and the unconstrained regime, in the regimes with binding CBDC constraints transaction costs per unit of consumption are not constant, but changes in consumption affect these costs. After a negative demand shock, for instance, households decrease their consumption expenditures, so that their demand for CBDC decreases. Consequently, the CBDC constraint becomes less binding, so that transaction costs per unit of consumption decrease. This dampens the effect of the shock. If the

central bank reacts to this shock, it will alleviate the constraint even further and thereby strengthen the dampening effects. Naturally, how strongly households benefit from the introduction and existence of a CBDC depends on their preference for CBDC holdings. Differing preferences thus imply that a CBDC in general and its use as a monetary policy instrument in particular have 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 implications of the introduction of a CBDC on business cycle dynamics. Barrdear and Kumhof (2022) utilize a New Keynesian model with a CBDC to examine, in particular, the macroeconomic effects of a transition to an economy with a CBDC as well as the effects of the existence of a CBDC on the transmission of shocks. They find that the issuance of a CBDC leads to an increase in GDP in steady state as well as to an improved stabilization after adverse shocks. Assenmacher et al. (2023) explicitly model the means-of-exchange function to examine business cycle implications. The authors find that the introduction of a CBDC mitigates the responses to adverse shocks by stabilizing the liquidity premium, i.e., the difference between the interest rate on CBDC and bank deposits relative to returns on government bonds. Mishra and Prasad (2023) analyze the relationship between cash and CBDC. To do so, they examine different government measures, such as the variation in the nominal rates of return on CBDC or the variation in the probability of detecting tax evasion. The authors find that cash and CBDC mainly differ in their transaction costs and that different government policies can influence the relative shares of cash and CBDC. Gross and Schiller (2021) use a money in the utility approach to analyze the implications of a CBDC on the banking sector. Another part of the literature addresses the implications of introducing a CBDC in an open economy. Bacchetta and Perazzi (2021) analyze the macroeconomic effects of a CBDC on the banking sector and find that a CBDC reduces distortions in an open economy. George et al. (2020) address the implications of a CBDC in a small open economy and they examine welfare effects of introducing a CBDC. Ferrari Minesso et al. (2022) assess the implications of a CBDC in an open economy in a two-country model. They find that a CBDC increases international linkages and spillover effects by creating a new arbitrage opportunity and therefore affecting optimal monetary policy in

the two countries examined asymmetrically. We contribute to this strand of the literature in the following ways. Whereas most papers study an interest-bearing CBDC and model a banking sector, we focus on a heterogeneous household sector and consider a CBDC that is not interest-bearing. This allows us to better reflect the planned institutional framework in the model. In addition, we specifically consider a CBDC as a medium of exchange by including transaction costs. Furthermore, we contribute to the literature by adding a heterogeneous household sector to study distributional effects of a CBDC.

Second, our paper is related to the literature on CBDC design and monetary policy. Several papers analyze different CBDC design options or specific design features like anonymity. Respective examples include Bech and Garratt (2017), Mancini-Griffoli et al. (2018), Allen et al. (2020), Assenmacher et al. (2021), Borgonovo et al. (2021), Kumhof and Noone (2021), Ahnert et al. (2022), Agur et al. (2022), and Auer et al. (2022). Another part of the literature focuses on the impact of CBDC on monetary policy and financial stability. Brunnermeier and Niepelt (2019) consider the relationship between public and private money and state an equivalence condition. Fernández-Villaverde et al. (2021) confirm these main equivalence results but the authors show the limits of this equivalence condition in the case of an impaired banking sector. Other papers stress monetary policy implications. Respective examples are Bjerg (2017), Bordo and Levin (2017), Engert and Fung (2017), Uhlig and Xie (2020), 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 this strand of the literature by assessing the role of heterogeneity in the introduction of a CBDC.

The paper is organized as follows. Section 2 describes the model. Section 3 details the model calibration and provides a steady state analysis of introducing different CBDC-regimes. Furthermore, within a dynamic analysis, we examine the consequences of a demand and a supply shock under different CBDC-regimes. Section 4 concludes.

²See 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 $k = H, L$, 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

$$U_t^k = Z_t \ln \left(C_t^k - \Psi^k C_{t-1}^k \right) - \chi \frac{N_t^{k1+\eta^k}}{1 + \eta^k}, \quad (1)$$

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

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

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

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

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

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

with β denoting the discount factor, subject to its budget constraint

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

The left hand side (LHS) of the household's budget constraint shows its nominal expenditures, consisting of its 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. Denoting a household's holdings of real money balances by m_t^k , this constraint is therefore given by

$$m_t^k = C_t^k \zeta_t^k. \quad (6)$$

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 demand for real money balances

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

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 allows to consider that high-income households may have a more pro-

nounced willingness to use CBDC than low-income households, as shown by, for example, Li (2022).

A household's total demand for money m_t^k will always be satisfied, i.e., total money supply always adjusts to the total demand. However, the central bank may limit the amount of CBDC each household is allowed to hold (as it is currently discussed in the euro area, for instance), i.e.,

$$0 \leq m_{CB,t}^k \leq m_{CB,t}^{max}. \quad (8)$$

If the constraint on CBDC holdings is binding, the total demand for money will be satisfied by a respective higher supply of conventional money, and the composition of overall real money holdings will deviate from the household's preferred mix.³ A household's actual mix of money holdings Γ_t^k is thus given by⁴

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

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 define these costs as transaction costs given by

$$T_t^k = (\zeta_t^k - 1) C_t^k, \quad (10)$$

with the transaction cost variable ζ_t^k being defined as

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

⁴A 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. Our approach thereby specifically captures the means of payments function of CBDC.

$$\zeta_t^k = 1 + \left(\Gamma_t^k - \Gamma_t^{uncon,k} \right)^2 \begin{cases} = 1 & \text{if } m_{CB,t}^k \leq m_{CB,t}^{max}, \\ > 1 \text{ and constant} & \text{if } m_{CB,t}^k > m_{CB,t}^{max} = 0, \\ > 1 \text{ and not constant} & \text{if } m_{CB,t}^k > m_{CB,t}^{max} > 0. \end{cases} \quad (11)$$

If the preferred mix of money holdings $\Gamma_t^{uncon,k}$ cannot be realized, $\zeta_t^k > 1$ and $T_t^k > 0$, i.e., household k will face transaction costs. This implies an increase in overall consumption expenditures $P_t \zeta_t^k C_t^k$, as online purchases, for instance, have to be replaced by in-store purchases. 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.

Transaction costs per unit of consumption are then given by $\frac{T_t^k}{C_t^k} =: AT_t^k = \zeta_t^k - 1$. Importantly, these costs are constant in the no-CBDC and the unconstrained regime, whereas they vary in the constrained and the monetary policy regime:

$$\frac{\partial AT_t^k}{\partial C_t^k} = \begin{cases} 0 & \text{if } m_{CB,t}^k \leq m_{CB,t}^{max}, \\ 0 & \text{if } m_{CB,t}^k > m_{CB,t}^{max} = 0, \\ \zeta_{C,t}^k > 0 & \text{if } m_{CB,t}^k > m_{CB,t}^{max} > 0, \end{cases} \quad (12)$$

with $\zeta_{C,t}^k$ denoting the change of the transaction cost variable in household k 's consumption. Intuitively, transaction costs per unit of consumption are at a maximum and constant in the no-CBDC regime as the share of conventional money is always unity. Conversely, AT_t^k is at a minimum and constant in the unconstrained regime as the household can always hold its preferred money mix. If CBDC exists and the constraint is binding, $\zeta_{C,t}^k > 0$, and transaction costs per unit of consumption will increase in consumption.⁵

⁵Formally, $\zeta_{C,t}^k > 0$ if $\frac{\partial m_{C,t}^k}{\partial C_t^k} > 0$. Intuitively, if the CBDC constraint is binding, the household will hold the maximum amount of CBDC possible. Consider then an increase in consumption: any additional consumption will lead to an increase in conventional money holdings and thereby the money mix of the household to further diverge from its optimal mix, increasing the household's transaction costs.

We now turn to the utility-maximizing behavior of the household. The first order conditions (FOCs) for a household's optimal mix of money holdings are

$$(\omega^k)^{\frac{1}{\varphi^k}} (m_{C,t}^k)^{-\frac{1}{\varphi^k}} \leq (1 - \omega^k)^{\frac{1}{\varphi^k}} (m_{CB,t}^k)^{-\frac{1}{\varphi^k}}, \quad (13)$$

$$\left[(1 - \omega^k)^{\frac{1}{\varphi^k}} (m_{CB,t}^k)^{-\frac{1}{\varphi^k}} - (\omega^k)^{\frac{1}{\varphi^k}} (m_{C,t}^k)^{-\frac{1}{\varphi^k}} \right] [m_{CB,t}^{max} - m_{CB,t}^k] = 0, \quad (14)$$

and

$$m_{CB,t}^{max} - m_{CB,t}^k \geq 0. \quad (15)$$

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 (13)) will equal those from CBDC holdings (RHS of (13)). 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 of CBDC the central bank sets.

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 $U_{c,t}^k \equiv \left(\frac{Z_t}{C_t^k - \Psi^k C_{t-1}^k} - \frac{\mathbb{E}_t[Z_{t+1}] \Psi^k \beta}{\mathbb{E}_t[C_{t+1}^k] - \Psi^k C_t^k} \right)$, the respective optimality conditions are

$$\chi^k N_t^k \eta^k = U_{c,t}^k \frac{W_t^k}{P_t} \Phi_t^k, \quad (16)$$

$$U_{c,t}^k = \beta(1 + i_t) \mathbb{E}_t \left[U_{c,t+1}^k \frac{P_t}{P_{t+1}} \frac{\Phi_{t+1}^k}{\Phi_t^k} \right], \quad (17)$$

with

$$\Phi_t^k \equiv \frac{1}{\zeta_t^k} - \frac{\zeta_{m_{C,t}}^k C_t^k}{m_{m_{C,t}}^k \zeta_t^k}, \quad (18)$$

where $\zeta_{m_{C,t}}^k$ denotes the change of the transaction cost variable in household k 's conventional money holdings, and $m_{m_{C,t}}^k$ is marginal total demand for money with respect to conventional money holdings given by

$$\zeta_{m_{C,t}}^k = 2(\Gamma_t^k - \Gamma_t^{uncon,k}) \frac{m_{CB,t}^k}{(m_{C,t}^k + m_{CB,t}^k)^2}, \quad (19)$$

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

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 (19). Intuitively, if households can hold as much CBDC as they wish, no transaction costs will be incurred, and equations (16) and (17) then represent the standard FOCs for a household's optimal amount of labor and the Euler equation.

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 expression $(1 - \Phi_t^k)U_{c,t}^k \frac{W_t^k}{P_t}$ thus reflects by 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 (18), this decrease will be more pronounced the more the household's actual mix of money holdings deviates from its preferred mix. Consequently, the lower the Φ_t^k , the more the household suffers from the imposed restriction. Equation (17) 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 to work and consume more in period t than in $t + 1$.⁶

The shared bond market implies risk sharing in the form of

$$U_{c,t}^k = \phi_t^k (U_{c,t}^{-k}) \frac{\Phi_t^{-k}}{\Phi_t^k}, \quad (20)$$

⁶Assume 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 (17).

with $\phi_t^k \equiv \frac{U_{c,SS}^k \Phi_{SS}^k}{U_{c,SS}^{-k} \Phi_{SS}^{-k}}$, where SS denotes the zero inflation steady state, $U_{c,SS}^k = \frac{1-\Psi^k \beta}{(1-\Psi^k) C_{SS}^k}$, and $-k$ the respective other household not captured by 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

$$Y_{j,t} = \left(\alpha N_{j,t}^H \frac{\varphi^N - 1}{\varphi^N} + (1 - \alpha) N_{j,t}^L \frac{\varphi^N - 1}{\varphi^N} \right)^{\frac{\varphi^N}{\varphi^N - 1}}, \quad (21)$$

with $\alpha > (1 - \alpha)$, ensuring higher wages for household H , 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

$$TC_{j,t} = A_t (w_t^H N_{j,t}^H + w_t^L N_{j,t}^L), \quad (22)$$

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

$$\frac{\alpha}{1 - \alpha} \left(\frac{N_{j,t}^H}{N_{j,t}^L} \right)^{-\frac{1}{\varphi^N}} = \frac{w_t^H}{w_t^L}. \quad (23)$$

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

$$\mathbb{E}_t \left[\sum_{\iota=0}^{\infty} \beta^\iota \Lambda^\iota \Omega_{t,t+\iota} \left(\frac{P_{j,t}}{P_{t+\iota}} Y_{j,t+\iota|t} - TC(Y_{j,t+\iota|t}) \right) \right], \quad (24)$$

subject to

$$Y_{j,t+\iota|t} = \left(\frac{P_{j,t}}{P_{t+\iota}} \right)^{-\theta} Y_{t+\iota}, \quad (25)$$

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

$$mc_t = \frac{A_t \left(w_t^H + w_t^L \left(\frac{1-\alpha}{\alpha} \frac{w_t^H}{w_t^L} \right)^{\varphi^N} \right)}{\left(\alpha + (1-\alpha) \left(\frac{1-\alpha}{\alpha} \frac{w_t^H}{w_t^L} \right)^{\varphi^N - 1} \right)^{\frac{\varphi^N}{\varphi^N - 1}}}. \quad (26)$$

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

$$p_t^* = \mu \frac{x_{1,t}}{x_{2,t}}, \quad (27)$$

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

$$x_{1,t} \equiv U_{c,t} Y_t mc_t + \Lambda \beta \mathbb{E}_t \left[\Pi_{t+1}^\theta x_{1,t+1} \right], \quad (28)$$

$$x_{2,t} \equiv U_{c,t} Y_t + \Lambda \beta \mathbb{E}_t \left[\Pi_{t+1}^{\theta-1} x_{2,t+1} \right], \quad (29)$$

where $U_{c,t} \equiv \kappa U_{c,t}^H + (1-\kappa)U_{c,t}^L$ and $\Pi_t \equiv \frac{P_t}{P_{t-1}}$. Equations (27), (28), and (29) 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 satisfies the households' demand for money, i.e., supplies money. It sets the nominal interest rate according to the following reaction function

$$i_t = \rho + \phi_{\pi,i} \pi_t, \quad (30)$$

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_t^S . The central bank adjusts m_t^S 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, $m_{CB,t}^{max}$, each household is allowed to hold. Naturally, the no-CBDC regime implies $m_{CB,t}^{max} = 0 \forall t$. 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 monetary policy regime. It is captured by

$$\log(m_{CB,t}^{max}) = \log(m_{CB,SS}^{max}) - \phi_{\pi,m} \log(\pi_t), \quad (31)$$

where $m_{CB,SS}^{max}$ 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.⁷ 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 negative inflation deviations from steady state).

2.4 Equilibrium

The goods market clears

$$Y_t = \zeta_t^H C_t^H + \zeta_t^L C_t^L, \quad (32)$$

⁷Naturally, implementing such a policy has to be technically feasible. Current discussions revolving around CBDCs seem to make considerations like ours possible. The ECB, for instance, plans to implement the digital euro via wallets that are most likely connected to the users bank account (Dombrovskis and Panetta, 2023). Thus, a decrease of the CBDC limit could be easily achieved. If necessary, the CBDC-amount held above the new limit could simply be transferred to the user's bank account ("waterfall approach", see Proposal for a Regulation of the European Parliament and of the Council on the establishment of the digital euro COM/2023/369 final.)

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

$$\int_0^1 N_{j,t}^k dj = N_t^k. \quad (33)$$

Bonds are in zero net supply

$$B_t^k + B_t^{-k} = 0. \quad (34)$$

The money market clears

$$m_t^S = m_t^k. \quad (35)$$

In particular, demand for conventional money is always satisfied:

$$m_{C,t}^S = m_{C,t}^k. \quad (36)$$

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

$$m_{CB,t}^S = \begin{cases} m_{CB,t}^k & \text{if } m_{CB,t}^k \leq m_{CB,t}^{max}, \\ m_{CB,t}^{max} & \text{if } m_{CB,t}^k > m_{CB,t}^{max}. \end{cases} \quad (37)$$

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 is set to 0.5,⁸ and the weight on conventional money of high income households to 0.5 (implying an equal weight on CBDC). In order

⁸Assenmacher 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.

to include the fact that low income households have a lower preference for CBDC (see Introduction), we set the weight on conventional money by household L to 0.8 (we address the relevance of this parameter for our results in Section 3.4). 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			
$\phi_{\pi,i}$	Central bank reaction coefficient: interest rate	1.5	Galí (2015)
$\phi_{\pi,m}$	Central bank reaction coefficient: CBDC	5	Analysis Parameter

Moreover, we assume that household H is more productive (implying higher income), and we set the elasticity of substitution between labor from households H and L to 2, thereby 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 central bank's reaction 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.⁹ Comparing the no-CBDC regime with

⁹In steady state, the monetary policy regime coincides with the constrained regime as monetary policy reacts to shocks only.

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 anymore. This means that no output has to be used to cover transaction costs, but total output is consumed.¹⁰ 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 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, but a limit on CBDC holdings is discussed (see Introduction). 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 .¹¹ The chosen CBDC limit corresponds to roughly two thirds of the households preferred level of CBDC holdings.¹²

¹⁰Note that despite the higher consumption per hour of work, households have no incentive to change their labor supply. In both the no-CBDC and the unconstrained regime, marginal transaction costs per unit of consumption are zero (see equation 12). Thus marginal benefit of work in equation (16) coincides in both regimes. To clarify this, we drop the indexes k and t and neglect habit formation ($\Psi = 0$) for the sake of simplicity. Then, in steady state, (16) 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 to $\chi N^\eta = \frac{W}{P} \frac{1}{C\zeta} = \frac{W}{P} \frac{1}{Y}$. The introduction of a CBDC in an unconstrained manner reduces ζ to one, i.e., total output is consumed. If the household worked more, marginal disutility of work (LHS) 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.

¹¹The qualitative results of our analysis would not change if both households were affected by the constraint.

¹²Note that as long as the CBDC constrained is binding, qualitatively, our results will not change if another limit is chosen. Furthermore, we control for household H 's preference for holding CBDC in Section 3.4.

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	1.10	1.25
$Y_{C,SS}$	Consumption-Relevant Output	1	1.06	1.17
Y_{SS}	Output	1	0.93	1
N_{SS}^L	Labor L	1	1	1
N_{SS}^H	Labor H	1	0.90	1
$m_{C,SS}^L$	Conventional Money Holdings L	1	0.77	0.80
$m_{C,SS}^H$	Conventional Money Holdings H	1	0.76	0.50
$m_{CB,SS}^L$	CBDC Holdings L	—	1	1.04
$m_{CB,SS}^H$	CBDC Holdings H	—	1	1.52
U_{SS}^L	Utility L	1	0.999	1.006
U_{SS}^H	Utility H	1	1.024	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. $Y_{C,SS} \equiv C_{SS}^L + C_{SS}^H$.

Table 2 reveals that also in this constrained regime, the introduction of a CBDC implies a higher utility for the constrained household H . The household consumes more and actually 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, it is crucial that in the constrained regime, household H can affect the transaction costs per unit of consumption by adjusting its level of consumption. The transaction costs per unit of consumption are no longer constant (see equation (12)). Due to this possibility, the household actually works less compared to the other regimes. To clarify this, we compare the constrained regime with the unconstrained regime. In the former, the household consumes less so that less money is needed. However, due to the binding constraint on CBDC holdings, the household reduces only its conventional money holdings. Consequently, the money mix held by household H moves closer to its preferred mix of money holdings which reduces its transaction costs per unit of consumption which are constant in the other regimes (see equation (12)). This implies that marginal utility of work decreases so that household H reduces its works even more.

By working less, less output is produced, but a higher share of total output can be used for consumption as fewer transaction costs are incurred.¹³

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 .¹⁴ 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 redistributive effects in this case. However, also in a constrained manner, the introduction of a CBDC implies an increase in economy-wide output, consumption, and 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 affecting both households symmetrically. The impulse responses are shown for the four different CBDC regimes. Independently of the regime, 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

¹³Formally, this is shown by the simplified version of equation (16) given in footnote 10. 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.

¹⁴Obviously, 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.

equation (12)), they are not affected by the shock. Naturally, in the unconstrained regime CBDC holdings decrease proportionally to overall and conventional money holdings.

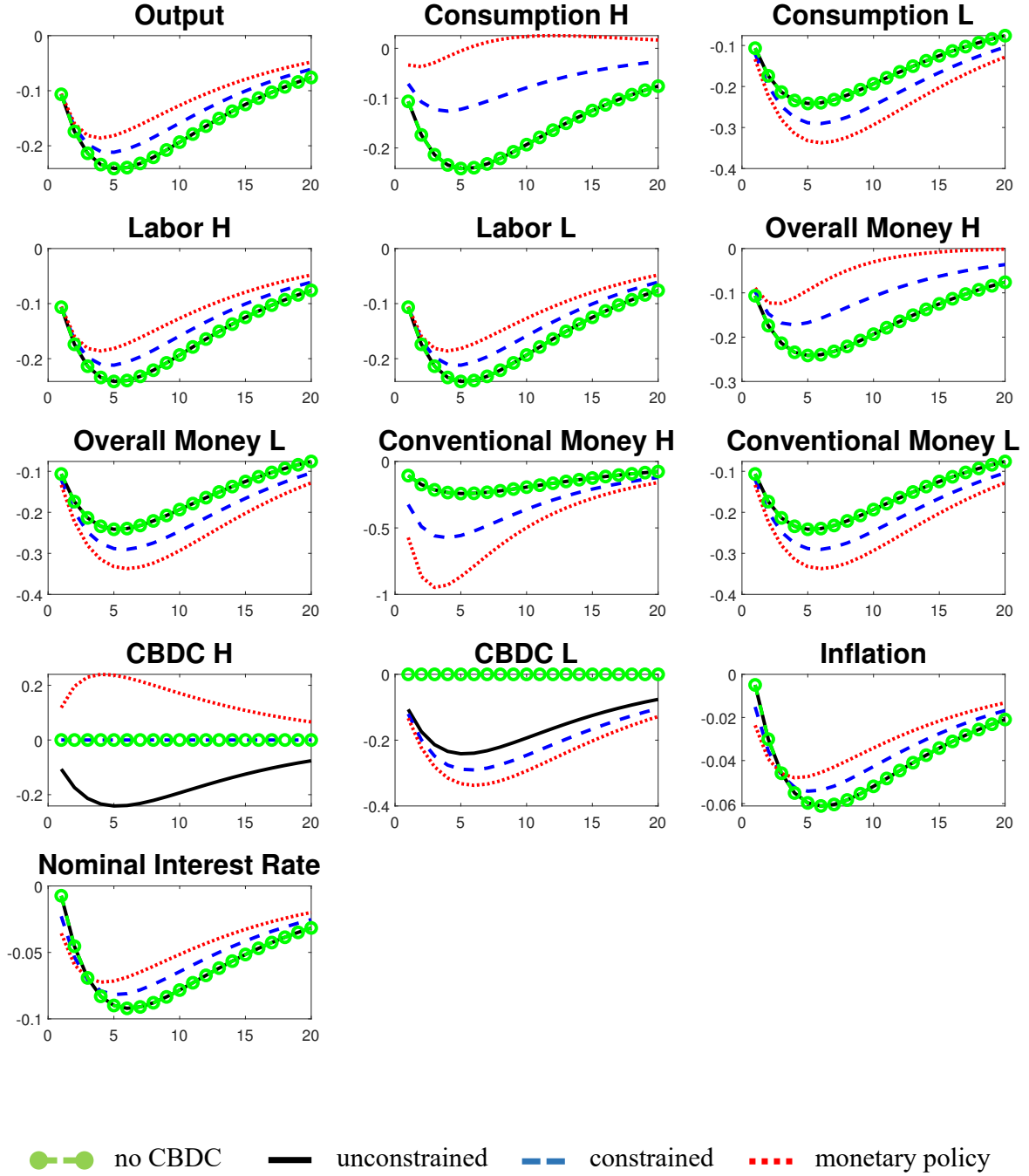


Figure 1: Impulse Responses to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$.

We proceed with comparing the impulse responses of the no-CBDC/unconstrained regime with the regimes in which CBDC holdings are limited (constrained/monetary policy). In the constrained/monetary policy 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, in the constrained and the monetary policy regime, deviations of output and inflation from their steady states are lower. The negative demand shock implies a decrease in money demand. However, as the constraint on CBDC holdings is still binding for household H , it reduces its conventional money only. Therefore, the household comes closer to its preferred mix of money holdings implying a decrease in its transaction costs per unit of consumption, which is the main difference between the constrained/monetary policy regime and the no-CBDC/unconstrained regime, where these costs are constant (see equation (12)). In the constrained/monetary policy regime, household H thus experiences a less pronounced shock-induced decrease in consumption. Consequently, output and thereby labor and inflation decrease less in this case. However, this occurs at the expense of household L 's consumption as a higher consumption of household H implies higher prices and a decrease in household L 's consumption. Overall, the shock absorption capabilities of the economy are strengthened in the constrained/monetary policy regime through the stabilization of household H 's consumption but household L 's consumption decreases even further.

Upon comparing the constrained regime with the monetary policy regime, we find that these effects are even more pronounced in the monetary policy 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, moving closer to its preferred mix of money holdings. 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 strengthens the redistributive effects of a CBDC limit.

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.

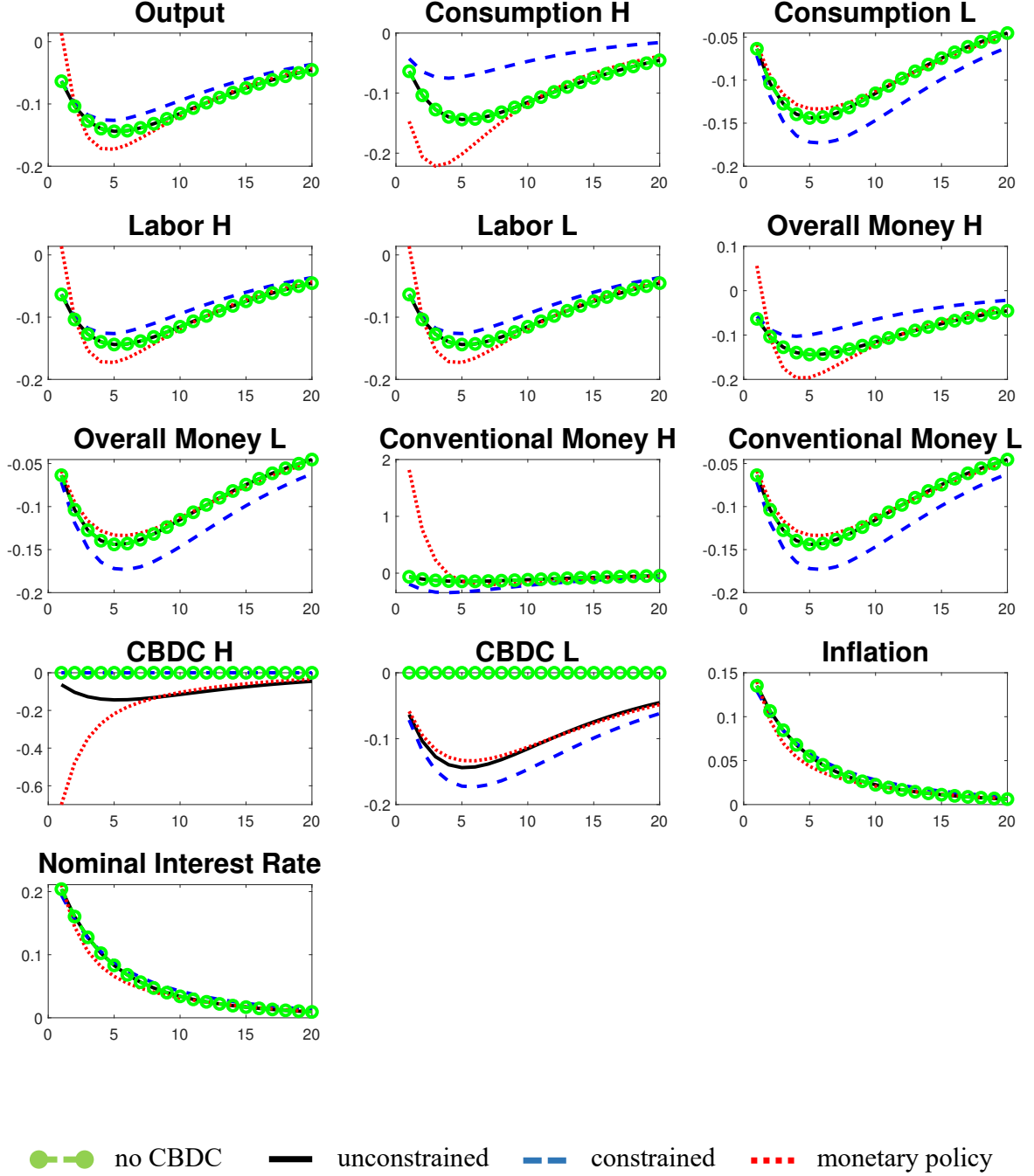


Figure 2: Impulse Responses to a 1% Cost-Push Shock (A^k) with Persistence $\rho_A = 0.9$.

In all cases, the increase in firms' costs 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 in the no-CBDC and the unconstrained regime (except for CBDC holdings).

Upon comparing the impulse responses of the constrained/monetary policy regime with the ones of the unconstrained/no-CBDC regime, we find that consumption of household H decreases less in the constrained/monetary policy regime. This is due to the possibility of household H to affect its transaction costs per unit of consumption. The decrease in consumption implies a lower money demand. However, household H reduces its conventional money holdings only as the CBDC limit is still 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 but prices increase even more. This leads household L to reduce its consumption more in the constrained/monetary policy regime.

In the monetary policy 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).¹⁵ Monetary policy thus has a stronger impact on inflation. However, this also amplifies the negative effects on output. In addition, using CBDC as a monetary policy instrument implies redistributive effects: the decrease in household H 's consumption and the corresponding lower increase in prices leads household L to decrease its consumption less strongly.

¹⁵Initially, output increases and then decreases less than in the other regimes due to the drastic decrease in transaction costs.

3.4 On the Relevance of CBDC Preferences

We continue with discussing the role of households' CBDC preferences for our results. We start with increasing the preference of household H for holding CBDC, i.e., we decrease ω^H from 0.5 (baseline calibration) to 0.4 while leaving the preferences of household L unchanged. This implies that the CBDC constraint becomes more binding for H . In the following, we compare the impulse responses to a negative demand (Figure 3) and a positive cost-push shock (Figure 4) for both values of ω^H under the monetary policy regime.

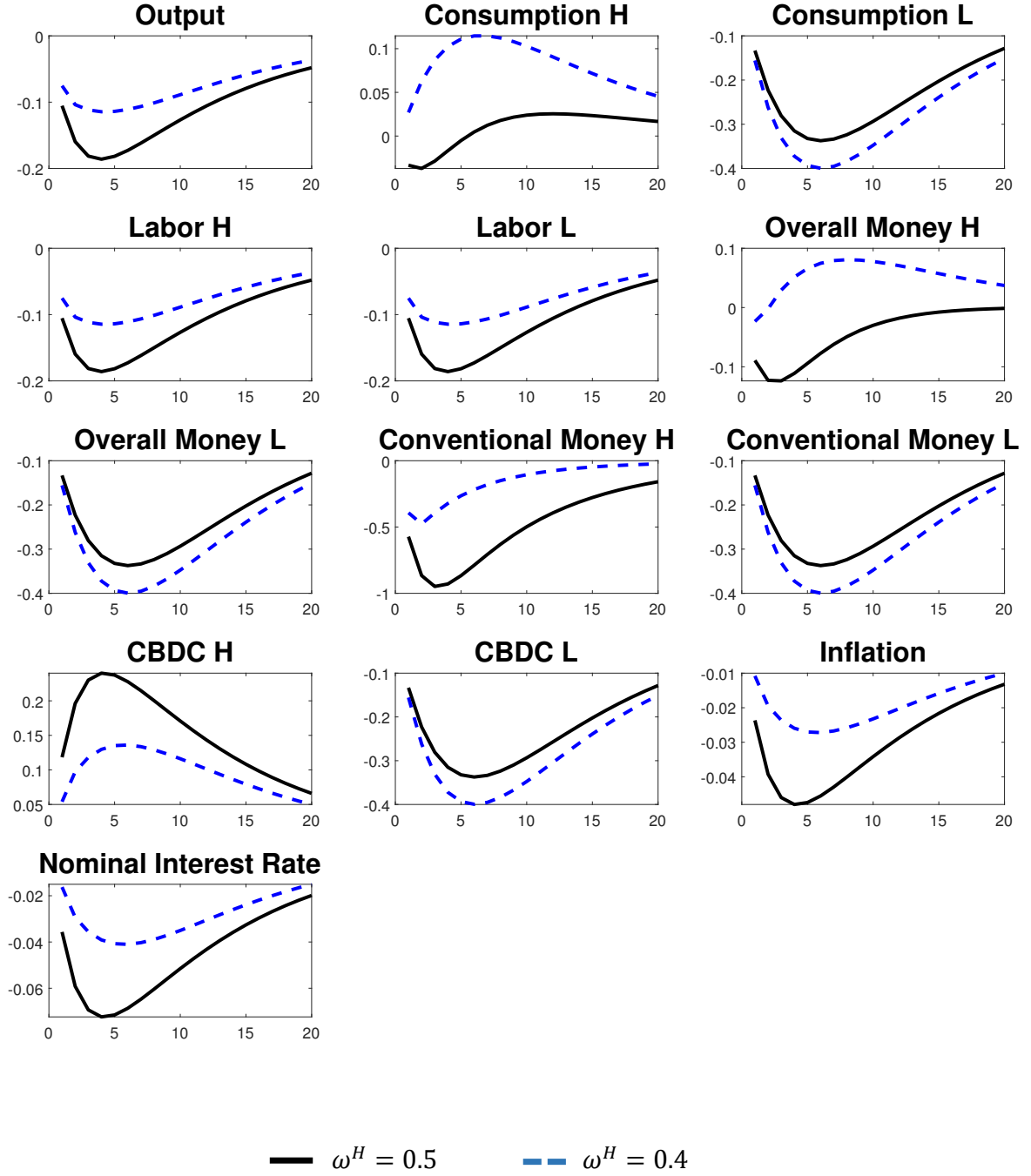


Figure 3: Impulse Responses in the Monetary Policy Regime to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$ for Different CBDC Preferences of household H .

After a negative demand shock, we find that using the CBDC limit as a monetary policy tool becomes even more effective in stabilizing prices when CBDC preferences are high. Simultaneously, redistributive effects between households increase. The intuition

behind these results is simple: The more binding the constraint on CBDC is, the larger are the positive effects of alleviating the constraint. In particular, the central bank increases the CBDC limit in response to the decline in inflation. Household H increases its CBDC holdings, which, in turn, decreases its transaction costs per unit of consumption. This decrease in these costs is larger, the higher the preference for CBDC is, i.e., the more binding the constraint is for a household. Thus, household H even increases its consumption after the negative demand shock when CBDC preferences are high. This implies a less pronounced decrease in overall output and inflation. The lower drop in prices leads household L to decrease consumption even more strongly, implying larger redistributive effects of monetary policy. Overall, the effects of using the CBDC limit as a monetary policy tool are amplified by a higher preference for CBDC of the constrained household.

Upon comparing the impulse response functions to a cost-push shock we find similar results: the effects of using the CBDC limit as a monetary policy tool are amplified in comparison to the baseline calibration when increasing the preference for CBDC of the constrained household. As prices increase after the shock, the central bank decreases the CBDC limit. Household H has to decrease its CBDC holdings, which increases transaction costs per unit of consumption for household H – more so when its CBDC preference is higher. Household H decreases its consumption even more, leading to a larger drop in output and a lower increase in prices when the CBDC preference of household H is higher. Household L , conversely, benefits from this muted increase in prices by decreasing its consumption less. Overall, the effects of using the CBDC limit as a monetary policy tool are again amplified by a higher CBDC preference of the constrained household.

Finally, we assume that both households have the same preferences for CBDC, i.e., $\omega^k = 0.5$. We find no differences in the responses to either of the shocks. This is an intuitive result: In the case of equal preferences the CBDC constraint is, naturally, still binding for household H . While household L now has the same preferences as H it still has lower income, implying that the CBDC constraint does not bind – as it was the case in the baseline calibration. Therefore, the responses to both shocks of both households does not change (apart from the composition of total money held by household L).

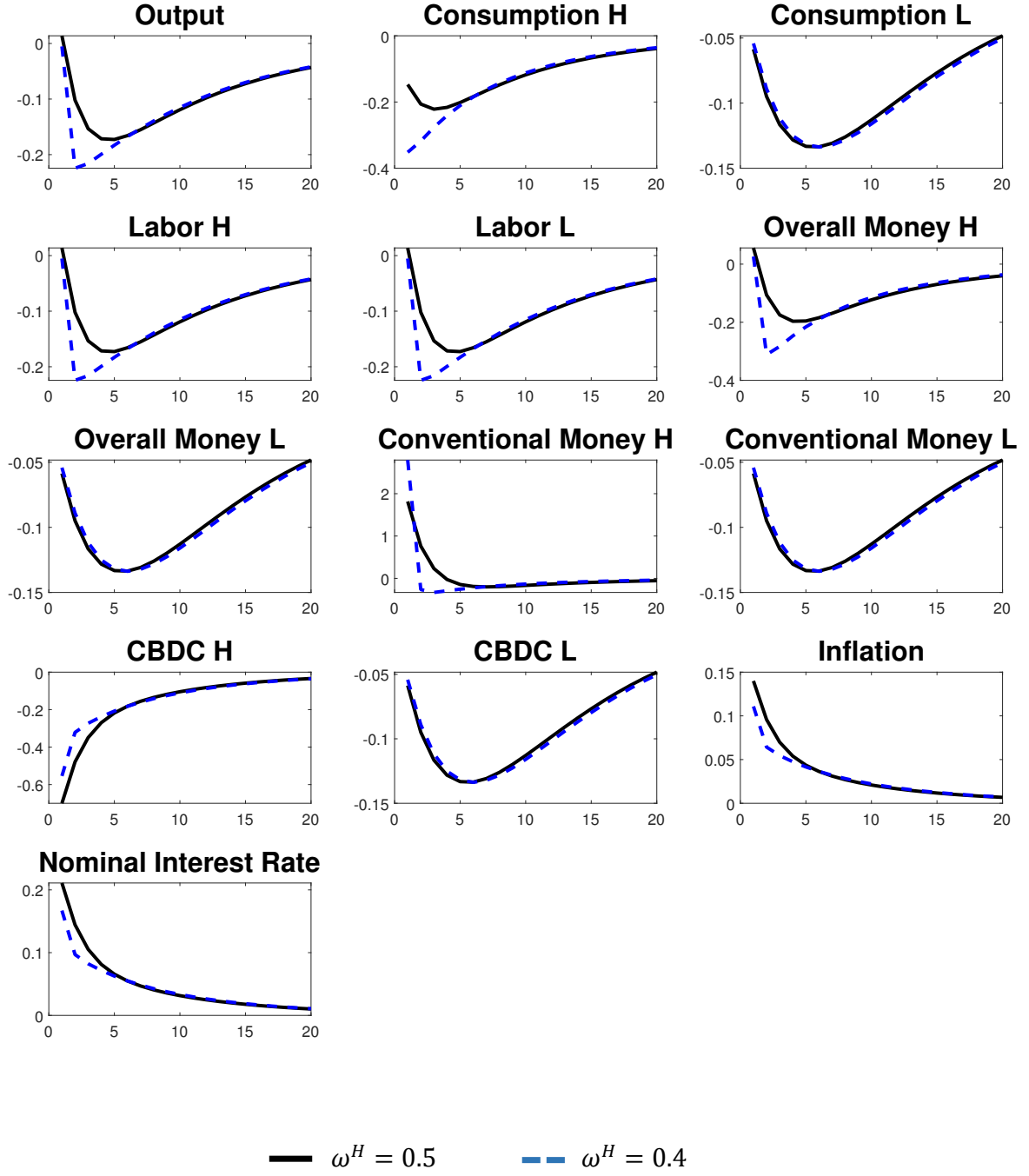


Figure 4: Impulse Responses in the Monetary Policy Regime to a 1% Cost-Push Shock (A^k) with Persistence $\rho_A = 0.9$ for Different CBDC Preferences of household H .

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 addition, households differ in their demand for a 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 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, 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 shocks.

We find that the introduction of a CBDC leads to a higher economy-wide utility in steady state. Moreover, the shock absorption capability will increase if CBDC is introduced in a constrained manner. The main driver for these results are transaction costs, as the introduction of a CBDC lowers the transaction costs per unit of consumption. In addition, changes in these transaction costs per unit of consumption lead to an improved shock absorption capability in the regimes with binding CBDC constraints, i.e., the central bank can stabilize prices more effectively. This particularly applies to the fourth CBDC regime where the central bank can change the maximum amount of CBDC each household is allowed to hold. Generally, introducing CBDC in a constrained manner and using the CBDC limit as a monetary policy instrument implies distributional effects across households.

Our findings raise questions for monetary policy implementation 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 as well as considering a heterogeneous monetary union model within our framework seems interesting for future research.

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