Cash or Cache? Distributional and Business Cycle Implications of CBDC Holding Limits*

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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 and distributional effects of different CBDC regimes in a New Keynesian model with a heterogeneous household sector. Households prefer to hold parts of their income in CBDC as a means of payment as it facilitates transactions. If they cannot hold their preferred share of CBDC they will face transaction costs. We find that the introduction of a CBDC increases economy-wide utility as it allows for higher consumption. Moreover, a binding limit on CBDC holdings increases the shock absorption capability of the economy. If this limit is used as a monetary policy instrument, prices will be stabilized more effectively after shocks. However, a CBDC may imply distributional effects across households, depending on the regime.

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

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1 Introduction

Central banks worldwide consider and debate the introduction of a Central Bank Digital Currency (CBDC).[1] 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 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). In this context, Bordo and Levin (2017) emphasize that a CBDC can facilitate payment transactions. In the same vein, central banks point out that the potential introduction of a CBDC aims at offering the broader public an additional means of payment as opposed to an additional means to store value (Panetta, 2022). Planned design features, such as non-interest bearing and limited CBDC holdings, underline the strong focus on the payment function of a CBDC.[2] Existing studies identify a demand for a CBDC (Deutsche Bundesbank, 2021b; Bijlsma et al., 2024) but households differ in the extent to which they want to hold CBDC depending on their socioeconomic status (Li, 2023; Meyer and Teppa, 2024). For instance, households with relatively low income tend to have a lower preference for digital payment options than households with relatively high income.

Against this background, this paper analyzes macroeconomic and distributional effects of the introduction of a CBDC as an additional means of payment in a New Keynesian model with a heterogeneous household sector. Our main results 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, i.e., to introduce a CBDC in a constrained manner, improves the shock absorption capability of the economy. (iii) Using the CBDC

[1]For an overview of the reasons for introducing a CBDC and design options see, for example, , Bank for International Settlements (2018), Adrian and Mancini-Griffoli (2021), Roesl and Seitz (2022), and Goodell et al. (2024). With respect to the current (July 2024) stage of the introduction of a digital euro see European Central Bank (2023) and the "Proposal for a Regulation of the European Parliament and of the Council on the establishment of the digital euro COM/2023/369 final".

[2]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; Fegatelli, 2022; Bellia and Calès, 2023; Kumhof et al., 2023; Muñoz and Soons, 2023). For an investigation of how a CBDC might affect the stability of the banking system and potential bank runs see Keister and Monnet (2022), Azzone and Barucci (2023), and Luu et al. (2023).

limit 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.

We reach these conclusions by considering four different CBDC regimes within our model. In the first regime, no CBDC exists ("no-CBDC regime"). In the second regime, each household may hold an unlimited amount of CBDC ("unconstrained regime"). In the third regime, the central bank sets a maximum amount of CBDC each household is allowed to hold ("constrained regime"). In the fourth regime, the central bank uses the CBDC as a monetary policy instrument by adjusting the limit ("monetary policy regime"). We capture the intended exclusive means of payment function of a CBDC in several ways: CBDC holdings are not interest bearing, they can be limited by the central bank, and they can only be used to buy consumption goods. We consider the main advantage of using CBDC, namely the facilitation of payment transactions, by introducing transaction costs. If households are not able to hold as much CBDC as they want to hold, i.e., if their actual share of CBDC holdings in their overall holdings is below their optimal share, they will face transaction costs. These costs may be interpreted as a sort of shoe-leather costs, as households have to replace online purchases by an in-store alternative, for example.

Transaction costs are the main driver for our results. In the no-CBDC regime, households face transaction costs, i.e., part of their income has to be used to pay for these costs and cannot be used for utility-increasing consumption. The introduction of a CBDC thus decreases transaction costs, allows for higher consumption and, therefore, increases utility. A binding limit on CBDC holdings implies that households' transaction costs per unit of consumption change in the consumption level: If households consume less, they will need less money. However, as long as the constraint on CBDC holdings is binding, they reduce their conventional money holdings only. Consequently, households get closer to their preferred mix of money holdings and transaction costs per unit of consumption decrease. This is the driving force behind the improved shock absorption capability under the regimes with binding CBDC constraints. After a negative demand shock, for instance, households reduce their consumption expenditures. Consequently, their demand for money decreases. However, due to the binding constraint on CBDC holdings, households decrease their conventional money holdings only, the CBDC constraint becomes less binding, and transaction costs per unit of consumption decrease. This dampens the effect of the shock. If the central bank uses the CBDC limit as a monetary policy instrument, 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 imply that holding limits on CBDC in steady state and, in particular, the use of these limits as a monetary policy instrument after adverse shocks have distributional effects across households.

This paper relates to the 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 to examine the macroeconomic effects of a transition to an economy with 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. They 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 (2024) analyze trade-offs between cash and CBDC. They find that these two forms of universally accessible central bank money mainly differ in their transaction efficiency and that different government measures can influence the relative shares of cash and CBDC holdings. 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 (2022) 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) examine welfare effects of introducing a CBDC in a small open economy. Ferrari Minesso et al. (2022) assess the implications of a CBDC 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 asymmetrically. Assenmacher et al. (2024) extend this model by including financial frictions. The authors find that the introduction of a CBDC improves welfare. However, macroeconomic volatility increases in the case of higher steady-state demand for CBDC. These effects can be mitigated by policies such as binding caps on CBDC holdings. We contribute to this first strand of the literature in the following ways. Whereas many papers study interest-bearing CBDC holdings (and thus also consider CBDC as a means of store of value) that cannot be limited by the central bank, we take a more realistic approach. We consider a CBDC that is not interest-bearing and potentially limited in its holdings, as it is planned in the euro area, for example. This allows us to explicitly consider the medium of exchange function of a CBDC, the function that is also explicitly put forward by the ECB, for instance. In addition, we contribute to this 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: 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 this literature focuses on the impact of specific CBDC design features on 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 include 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 use of the maximum amount of CBDC each household is allowed to hold 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).[3] We contribute to this strand of the literature by assessing the

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

distributional effects of a CBDC as well as the relevance of household heterogeneity for the impact of a CBDC on macroeconomic outcomes.

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 and analyze the role of household heterogeneity. Section 4 concludes.

2 Model

2.1 Households

The household sector consists of a continuum of households with two types $k = H, L$. Household H is a representative household with high income and household L a representative 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

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

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

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

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

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

The left hand side (LHS) of the household's budget constraint shows its nominal expenditures, consisting of its expenditures for consumption $P_t \left(1 + \zeta_t^k\right) C_t^k$ and for one-period, risk-free bonds B_t^k at price unity. The term $\zeta_t^k C_t^k \geq 0$ reflects that transaction costs are potentially incurred when buying goods. These transactions costs play a crucial role in our analysis. 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

$$m_t^k = C_t^k \left(1 + \zeta_t^k\right). \tag{6}$$

A household has the possibility to hold conventional money (cash and deposits) and CBDC. As we primarily focus on the means of payment function of money, we aggregate cash and deposits.[4] In this context, we are interested in the substitutability of CBDC (as a new means of payment) in relation to traditional forms of money in general.[5] We assume that each household wants to hold a specific mix of these two types of money. Denoting real conventional money holdings by $m^k_{C,t}$ and real CBDC holdings by $m^k_{CB,t}$, we capture the household's money holdings preference by the following CES function for a household's demand for real money balances

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

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 allows to consider that high-income households may have a more pronounced willingness to use CBDC than low-income households, as shown by, for example, Li (2023) and Meyer and Teppa (2024).

A household's total demand for money m^k_t 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.,

$$0 \leq m^k_{CB,t} \leq m^{max}_{CB,t}. \tag{8}$$

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

[4] One could similarly think of households that assign the same preference to cash and deposits, implying that separating the two forms of money yields the same results as aggregating them.

[5] CBDC can be seen as a new means of payment that substitutes cash in some transactions, replaces deposits in other transactions and enables otherwise forgone transactions.

money holdings will deviate from the household's preferred mix.[6] A household's actual share of conventional money holdings in its total money holdings Γ_t^k is thus given by[7]

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

with $\Gamma_t^{con,k}$ being the share of conventional money holdings in the total 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 transaction costs given by

$$T_t^k = \zeta_t^k C_t^k, \tag{10}$$

with ζ_t^k being defined as the deviation of actual money holdings from the optimal mix

$$\zeta_t^k = \left(\Gamma_t^k - \Gamma_t^{uncon,k}\right)^2 \begin{cases} = 0 & \text{if} \quad m_{CB,t}^k \leq m_{CB,t}^{max}, \\ > 0 \text{ and } \zeta_{C,t}^k = 0 & \text{if} \quad m_{CB,t}^k > m_{CB,t}^{max} = 0, \\ > 0 \text{ and } \zeta_{C,t}^k > 0 & \text{if} \quad m_{CB,t}^k > m_{CB,t}^{max} > 0, \end{cases} \tag{11}$$

with $\zeta_{C,t}^k$ denoting the change of this deviation in household k's consumption. If the preferred mix of money holdings $\Gamma_t^{uncon,k}$ cannot be realized, i.e., if $\zeta_t^k > 0$ and $T_t^k > 0$, household k will face transaction costs.[8] This implies an increase in overall consumption expenditures $P_t\left(1+\zeta_t^k\right)C_t^k$, 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

[6]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.

[7]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. Our approach thereby specifically captures the means of payments function of CBDC.

[8]Note that we assume the functional form of transaction costs to resemble other types of commonly used cost functions, such as price and capital adjustment costs, or balance sheet and management costs. Naturally, we cannot comment on the size of these transaction costs in reality due to the lack of data on CBDC holdings. However, our results remain qualitatively unaffected by the size of these costs.

transactions not undertaken by a household due to the unavailability of the preferred payment option. Note that the quadratic form of equation (11) implies that transaction costs increase disproportionately in the deviation of the actual mix of money holdings from the preferred mix.

Transaction costs per unit of consumption given by $\frac{T_t^k}{C_t^k} =: AT_t^k = \zeta_t^k$ are constant in the no-CBDC and the unconstrained regime, whereas they vary in the constrained and the monetary policy regime. 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 zero in the unconstrained regime as the household can always hold its preferred money mix. If a CBDC exists and if there is a binding constraint on CBDC holdings, transaction costs per unit of consumption will increase in consumption. The binding constraint implies that the household will hold the maximum amount of CBDC possible. An increase in consumption then implies an increase its conventional money holdings only. The household's mix of money holdings will deviate even more from its preferred mix, and transaction costs per unit of consumption will increase.

The first order conditions (FOCs) for a household's optimal mix of money holdings are[9]

$$(\omega^k)^{\frac{1}{\varphi^k}} \left(m_{C,t}^k\right)^{-\frac{1}{\varphi^k}} \leq (1-\omega^k)^{\frac{1}{\varphi^k}} \left(m_{CB,t}^k\right)^{-\frac{1}{\varphi^k}}, \tag{12}$$

$$\left[(1-\omega^k)^{\frac{1}{\varphi^k}} \left(m_{CB,t}^k\right)^{-\frac{1}{\varphi^k}} - (\omega^k)^{\frac{1}{\varphi^k}} \left(m_{C,t}^k\right)^{-\frac{1}{\varphi^k}}\right] \left[m_{CB,t}^{max} - m_{CB,t}^k\right] = 0, \tag{13}$$

and

$$m_{CB,t}^{max} - m_{CB,t}^k \geq 0. \tag{14}$$

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 (12)) will equal those from CBDC holdings (RHS of (12)). However, if the constraint is

[9]Although we do not explicitly model costs attached to demanding and receiving conventional money or CBDC, we assume that households aim to reach a given level of overall money holdings in the most efficient, i.e., "cost-minimizing" way according to their preferences.

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

$$\chi^k N_t^{k\eta^k} = U_{c,t}^k \frac{W_t^k}{P_t} \Phi_t^k, \tag{15}$$

$$U_{c,t}^k = \beta(1+i_t)\,\mathbb{E}_t \left[U_{c,t+1}^k \frac{P_t}{P_{t+1}} \frac{\Phi_{t+1}^k}{\Phi_t^k} \right], \tag{16}$$

with

$$\Phi_t^k \equiv \frac{1}{1+\zeta_t^k} - \frac{\zeta_{m_{C,t}}^k C_t^k}{m_{m_{C,t}}^k \left(1+\zeta_t^k\right)}, \tag{17}$$

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

$$\zeta_{m_{C,t}}^k = 2(\Gamma_t^k - \Gamma_t^{uncon,k}) \frac{m_{CB,t}^k}{(m_{C,t}^k + m_{CB,t}^k)^2}, \tag{18}$$

$$m_{m_{C,t}}^k = \left(m_t^k\right)^{\frac{1}{\varphi^k}} (\omega^k)^{\frac{1}{\varphi^k}} \left(m_{C,t}^k\right)^{-\frac{1}{\varphi^k}}. \tag{19}$$

If the constraint on CBDC holdings is not binding, no transaction costs will be incurred, $\zeta_t^k = 0$ and $\Phi_t^k = 1$, since $\zeta_{m_{C,t}}^k = 0$ as shown by equation (18). Intuitively, if households can hold as much CBDC as they wish, no transaction costs will be incurred, and equations (15) and (16) 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 ($\zeta_t^k > 0$ and $\Phi_t^k < 1$) and the optimal behavior of the household will change. The marginal utility of work decreases as part of the wage cannot be used any longer to pay for beneficial consumption but has to be used to pay 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 (17), 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 (16) 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 $t+1$.[10]

The shared bond market implies risk sharing in the form of

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

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, $U_{c,SS}^k = \frac{1-\Psi^k\beta}{(1-\Psi^k)C_{SS}^k}$, 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

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

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.

[10]Assume 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 (16).

Firm j's real total costs are given by

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

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

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

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

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

subject to

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

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

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

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

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

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

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

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

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 expected future marginal costs and the expected development of the price level.

2.3 Central Bank

The central bank sets the nominal interest rate and satisfies households' demand for money, i.e., it supplies money. It sets the nominal interest rate according to the following reaction function

$$i_t = \rho + \phi_{\pi,i}\pi_t, \tag{30}$$

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 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

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

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 monetary policy regime, $\phi_{\pi,m} > 0$, i.e., the central bank adjusts the CBDC limit according to the inflation development in the economy.[11] For instance, when the central bank observes inflation, it decreases the quantity of CBDC that households are allowed to hold.[12] 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 devations from steady state).

2.4 Equilibrium

The goods market clears

$$Y_t = \left(1 + \zeta_t^H\right) C_t^H + \left(1 + \zeta_t^L\right) C_t^L, \tag{32}$$

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

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

Bonds are in zero net supply

$$B_t^k + B_t^{-k} = 0. \tag{34}$$

The money market clears

$$m_t^S = m_t^k. \tag{35}$$

[11]In our model, this implies that the central bank reacts to inflation with two different measures. In reality, the interest rates set by a central bank naturally depend on many different factors and the monetary policy toolbox consists of many different instruments. Thus, we are interested in examining the addition of the CBDC limit to this existing toolbox, i.e., the Taylor rule in our model.

[12]Naturally, 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 the "Proposal for a Regulation of the European Parliament and of the Council on the establishment of the digital euro COM/2023/369 final".)

In particular, demand for conventional money is always satisfied:

$$m_{C,t}^{S} = m_{C,t}^{k}. \tag{36}$$

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:

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

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,[13] 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 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).

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).

[13] 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. We check the robustness of our results with respect to this parameter choice in Appendix A.

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

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.[14] 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.[15] 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. 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

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

[15]Note that despite the higher consumption per hour of work, households have no incentive to change their labor supply. 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, (15) reduces to $\chi N^{\eta} = \frac{W}{P}\frac{1}{C(1+\zeta)}\left(1 - \frac{\zeta_{m_C} C}{m_{m_C}}\right) = \frac{W}{P}\frac{1}{Y}\left(1 - \frac{\zeta_{m_C} C}{m_{m_C}}\right)$, and in the no-CBDC regime as well as in the unconstrained regime to $\chi N^{\eta} = \frac{W}{P}\frac{1}{C(1+\zeta)} = \frac{W}{P}\frac{1}{Y}$. The introduction of a CBDC in an unconstrained manner reduces ζ to zero, 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. See also footnote 18.

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.[16] The chosen CBDC limit corresponds to roughly two thirds of the households preferred level of CBDC holdings.[17]

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 the constrained regime, the introduction of a 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 ($\zeta_t^H > 0$), so that the increase in consumption after the introduction of a CBDC is lower than in the unconstrained regime. Crucially, in comparison to the other regimes, the constrained household

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

[17]Note that as long as the CBDC constraint 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.

H actually works less.[18] This behavior allows it to reduce its transaction costs per unit of consumption, i.e., to use a higher share of its income for utility-increasing consumption: Working less implies a lower income and a decrease in consumption. Consequently, the household needs less money. Due to the constraint it reduces its conventional money holdings only. The share of CBDC holdings in its total money holdings increases and transaction costs decrease. Consequently, the household uses a larger share of its income for utility-increasing consumption. In the other regimes this possibility does not exist.[19]

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.[20] 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 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

[18] Formally, the simplified version of equation (15) $\chi N^\eta = \frac{W}{P}\frac{1}{C(1+\zeta)}\left(1 - \frac{\zeta_{m_C} C}{m_{m_C}}\right) = \frac{W}{P}\frac{1}{Y}\left(1 - \frac{\zeta_{m_C} C}{m_{m_C}}\right)$ (see footnote 15), reveals that optimal behavior requires that the household will reduce its labor supply if a constraint on CBDC holdings is introduced. In the no-CBDC regime as well as in the unconstrained regime the term $1 \geq \left(1 - \frac{\zeta_{m_C} C}{m_{m_C}}\right) > 0$ equals one, i.e., in both regimes optimality requires the same labor supply (see footnote 15). However, if there is a binding constraint, the term is strictly smaller than 1. Hence, the introduction of a binding constraint on CBDC holdings causes marginal utility of work to be higher than marginal utility. This implies a reduction in the household's labor supply.

[19] In the no-CBDC regime, the share of CBDC holdings in total money holdings is always zero, and in the unconstrained regime there are no transaction costs that can be reduced.

[20] 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.

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.

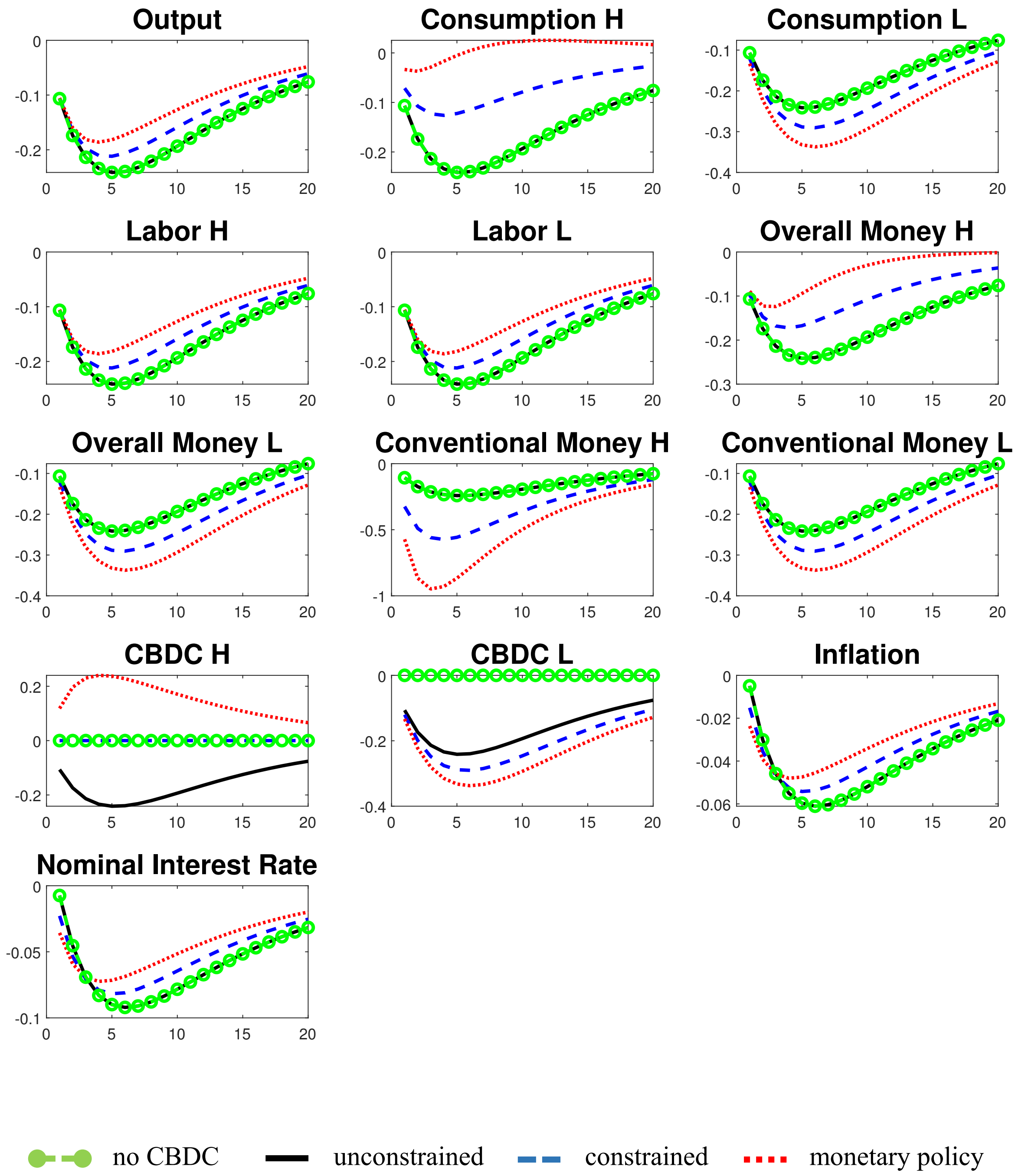

Figure 1: Impulse Responses to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$.

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 equation (11)), they are not affected by the shock. Naturally, in the unconstrained regime CBDC holdings decrease proportionally to overall and conventional money holdings.

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 binding 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 gets 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 (11)). 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 redistributional 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. 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).[21] Monetary policy thus has a stronger impact on inflation. However, this also

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

amplifies the negative effects on output. In addition, using CBDC as a monetary policy instrument implies redistributional effects: the decrease in household H's consumption and the corresponding lower increase in prices leads household L to decrease its consumption less strongly.

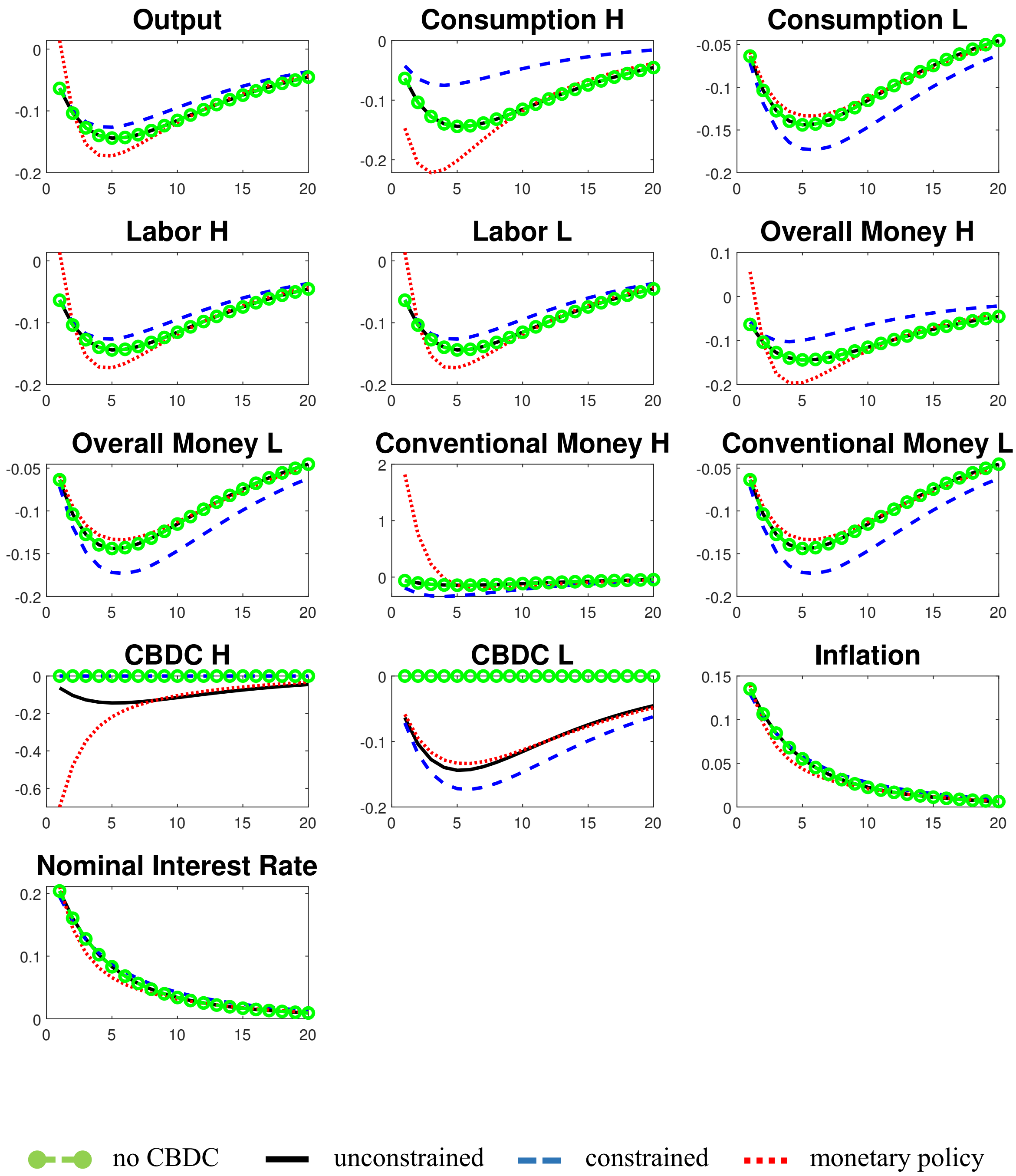

Figure 2: Impulse Responses to a 1% Cost-Push Shock (A_t^k) with Persistence $\rho_A = 0.9$.

3.4 On the Relevance of Household Heterogeneity in 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.

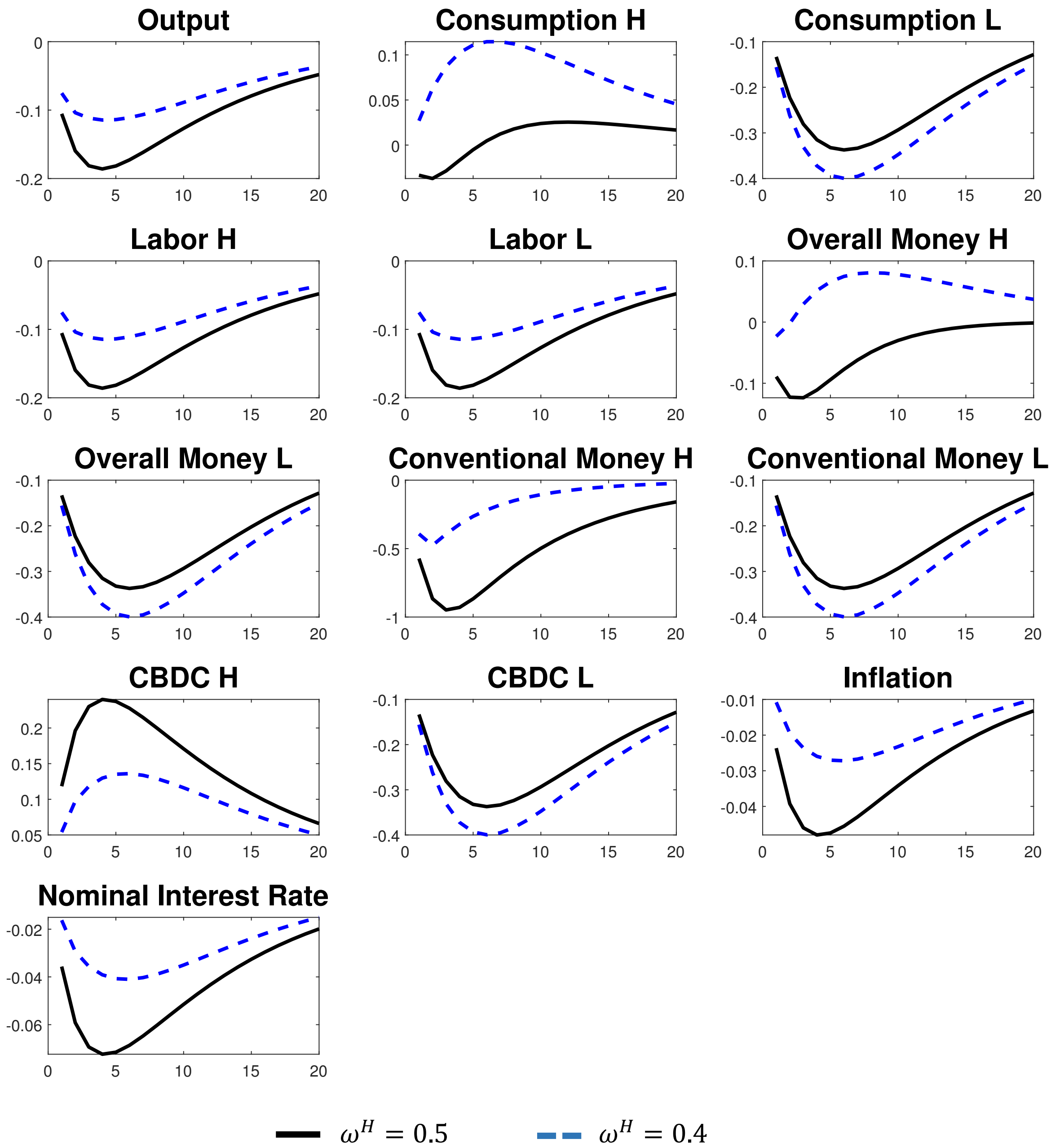

Figure 3: Impulse Responses in the Monetary Policy Regime to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$ for Different CBDC Preferences of Household H.

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.

After a negative demand shock, we find that using the CBDC limit as a monetary policy instrument becomes even more effective in stabilizing prices when CBDC preferences are high. Simultaneously, redistributional 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 redistributional effects of monetary policy. Overall, the effects of using the CBDC limit as a monetary policy instrument 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 instrument 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 instrument 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).

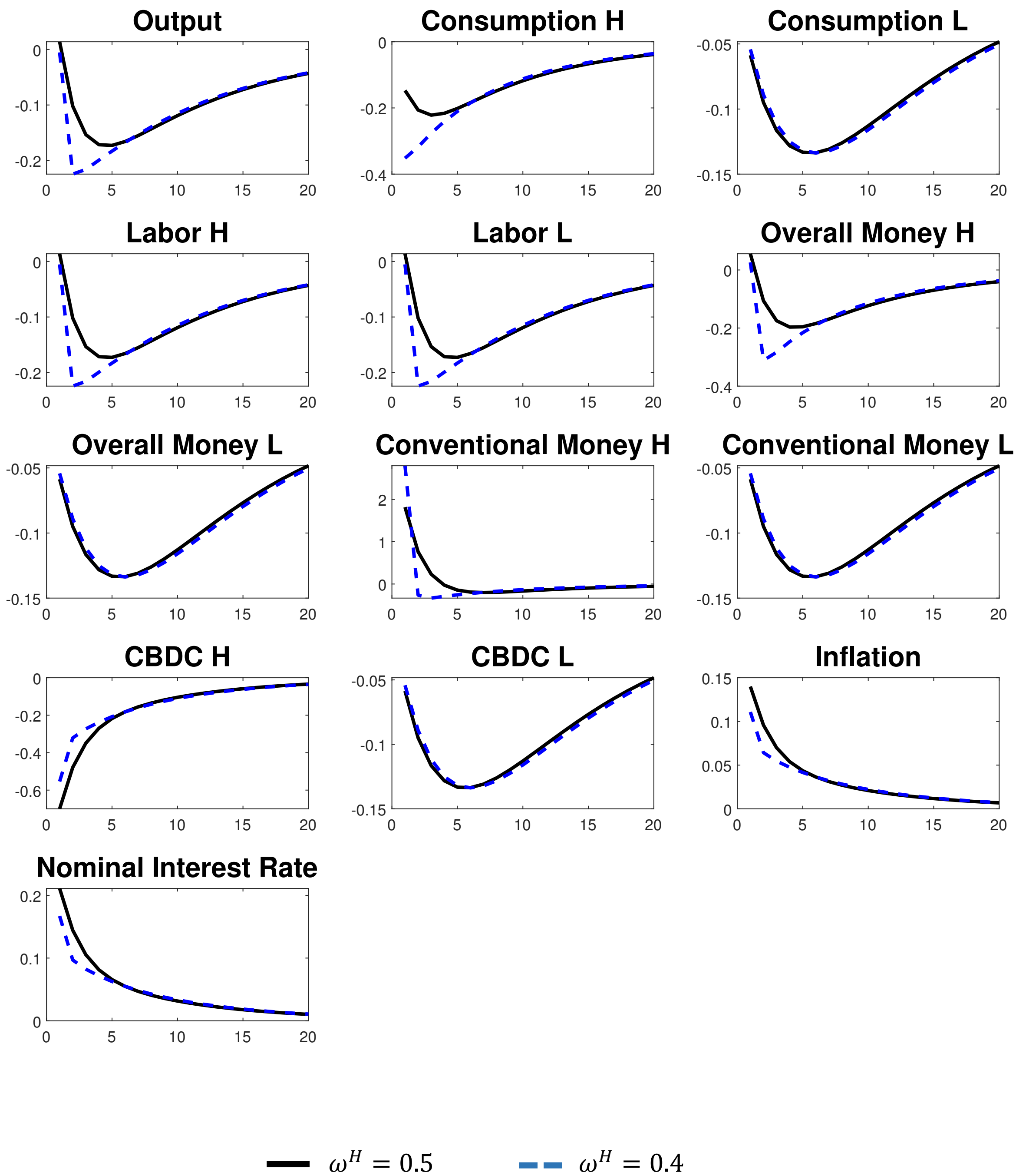

Figure 4: Impulse Responses in the Monetary Policy Regime to a 1% Cost-Push Shock (A_t^k) with Persistence $\rho_A = 0.9$ for Different CBDC Preferences of Household H.

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. CBDC serves as a means of payment for households. 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 limit to potentially stabilize prices after shocks.

We find that the introduction of a CBDC leads to a higher economy-wide utility in steady state. This is in line with the existing literature on the transition to an economy with CBDC. Moreover, the shock absorption capability will increases if CBDC is introduced in a constrained manner. The main driver for these results are transaction costs. The introduction of a CBDC lowers the transaction costs per unit of consumption. In the two regimes in which there is a limit on CBDC holdings, transaction costs per unit of consumption are no longer constant. This leads to an improved shock absorption capability in these regimes. Furthermore, by using the CBDC limit as a monetary policy tool, the central bank can stabilize prices more effectively. Generally, introducing CBDC and using the CBDC limit as a monetary policy instrument implies distributional effects across households.

Similar to other monetary policy instruments or the (theoretical) considerations on interest-bearing CBDC, the use of the CBDC holding limit as a monetary policy instrument involves drawbacks, such as a potential negative impact on the central bank's credibility. Furthermore, other transmission channels are possible, especially when including a banking sector.

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. Analyzing 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.

A Elasticity of Substitution

We check the robustness of our results derived in Section 3.3 with respect to the elasticity of substitution between conventional money and CBDC.

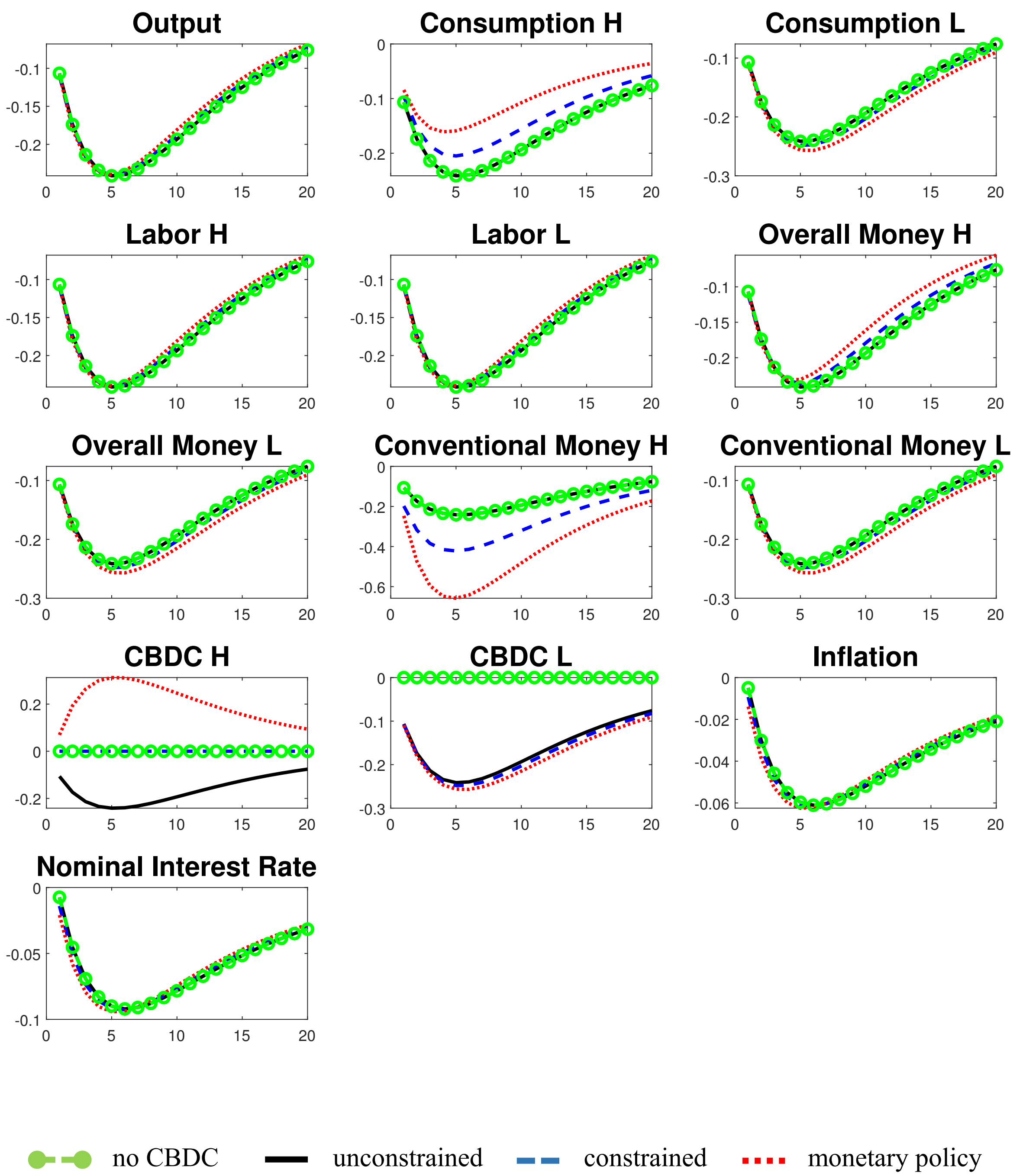

Figure A.1: Impulse Responses to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$ and Elasticity of Substitution Between Conventional Money and CBDC $\varphi_k = 1.5$.

While it is common to set the elasticity of substitution to 0.5 (see Section 3.1 and references therein), implying a relatively low degree of substitutability, our results remain qualitatively unchanged when considering a higher elasticity of substitution ($\varphi_k = 1.5$).

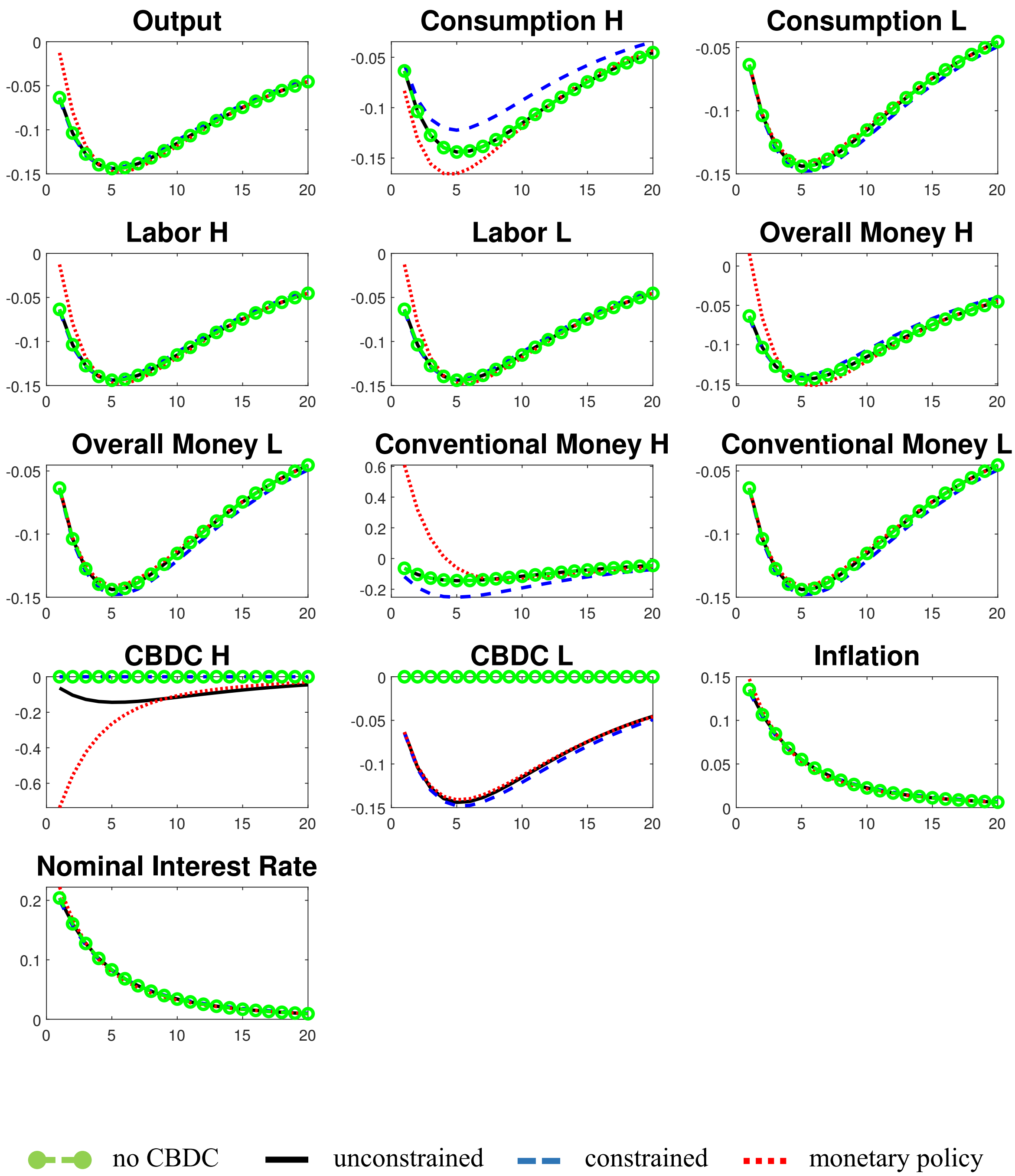

Figure A.2: Impulse Responses to a 1% Cost-Push Shock (A_t^k) with Persistence $\rho_A = 0.9$ and Elasticity of Substitution Between Conventional Money and CBDC $\varphi_k = 1.5$.

Intuitively, the effects of the constraint as well as the effectiveness of using the constraint as a monetary policy tool decreases in the elasticity of substitution as CBDC can be more easily substituted with conventional money. Therefore, reaching the necessary level of overall money holdings is easier for households, implying a less prominent role of transaction costs and the related effects on the outcomes.

Bibliography

Acemoglu, D. (2002). Directed technical change. *Review of Economic Studies 68*, 781–809. http://www.jstor.org/stable/1556722.

Adalid, R., l. Álvarez Blázquez, K. Assenmacher, L. Burlon, M. Dimou, C. López-Quiles, N. M. Fuentes, B. Meller, M. Muñoz, P. Radulova, C. R. d'Acri, T. Shakir, G. Šílová, O. Soons, and A. V. Veghazy (2022). Central bank digital currency and bank disintermediation. *ECB Occasional Paper Series No. 293*. https://doi.org/10.2866/467860.

Adrian, T. and T. Mancini-Griffoli (2021). The rise of digital money. *Annual Review of Financial Economics 13*, 57–77. https://doi.org/10.1146/annurev-financial-101620-063859.

Agur, I., A. Ari, and G. Dell'Ariccia (2022). Designing central bank digital currencies. *Journal of Monetary Economics 125*, 62–79. https://doi.org/10.1016/j.jmoneco.2021.05.002.

Ahnert, T., P. Hoffmann, and C. Monnet (2022). The digital economy, privacy, and CBDC. *ECB Working Paper Series No. 2662*. https://data.europa.eu/doi/10.2866/284946.

Albonico, A., L. Calés, R. Cardani, O. Croitorov, F. Di Dio, F. Ferroni, M. Giovannini, S. Hohberger, B. Pataracchia, F. Pericoli, P. Pfeiffer, R. Raciborski, M. Ratto, W. Roeger, and L. Vogel (2019). The global multi-country model (GM): An estimated DSGE model for euro area countries. *European Commission, European Economy Discussion Paper No. 102*. https://doi.org/10.2765/254908.

Allen, S., S. Čapkun, I. Eyal, G. Fanti, B. Ford, J. Grimmelmann, A. Juels, K. Kostiainen, S. Meiklejohn, A. Miller, E. Prasad, K. Wüst, and F. Zhang (2020). Design choices for central bank digital currency: Policy and technical considerations. *NBER Working Paper Series 27634*. https://doi.org/10.3386/w27634.

Assenmacher, K., A. Berentsen, C. Brand, and N. Lamersdorf (2021). A unified framework for CBDC design: remuneration, collateral haircuts and quantity constraints. *ECB Working Paper Series No. 2578*. https://doi.org/10.2866/964730.

Assenmacher, K., L. Bitter, and A. Ristiniemi (2023). CBDC and business cycle dynamics in a New Monetarist New Keynesian model. *ECB Working Paper Series No. 2811*. https://doi.org/10.2866/800536.

Assenmacher, K., M. Ferrari Minesso, A. Mehl, and M. S. Pagliari (2024). Managing the transition to central bank digital currency. *ECB Working Paper Series No. 2907*. https://doi.org/10.2866/968408.

Auer, R., J. Frost, L. Gambacorta, C. Monnet, T. Rice, and H. S. Shin (2022). Central bank digital currencies: Motives, economic implications, and the research frontier. *Annual Review of Economics 14*, 697–721. https://doi.org/10.1146/annurev-economics-051420-020324.

Azzone, M. and E. Barucci (2023). Evaluation of sight deposits and central bank digital currency. *Journal of International Financial Markets, Institutions and Money 88*, 101841. https://doi.org/10.1016/j.intfin.2023.101841.

Bacchetta, P. and E. Perazzi (2022). CBDC as imperfect substitute for bank deposits: A macroeconomic perspective. *Swiss Finance Institute Research Paper No. 21-81*. https://doi.org/10.2139/ssrn.3976994.

Bank for International Settlements (2018). Central bank digital currencies. *Committee on Payments and Market Infrastructures, Markets Committee Papers No. 174*. https://www.bis.org/cpmi/publ/d174.pdf.

Barrdear, J. and M. Kumhof (2022). The macroeconomics of central bank digital currencies. *Journal of Economic Dynamics and Control 142*, 104148. https://doi.org/10.1016/j.jedc.2021.104148.

Bech, M. and R. Garratt (2017). Central bank cryptocurrencies. *BIS Quarterly Review September 2017*, 55–70. https://www.bis.org/publ/qtrpdf/r_qt1709f.pdf.

Bellia, M. and L. Calès (2023). Bank profitability and central bank digital currency. *JRC Working Papers in Economics and Finance 2023/6*. https://publications.jrc.ec.europa.eu/repository/handle/JRC133796.

Bijlsma, M., C. van der Cruijsen, N. Jonker, and J. Reijerink (2024). What triggers consumer adoption of central bank digital currency? *Journal of Financial Services Research 65*, 1–40. https://doi.org/10.1007/s10693-023-00420-8.

Bjerg, O. (2017). Designing new money - the policy trilemma of central bank digital currency. *Copenhagen Business School, CBS MPP Working Paper 06/2017*. https://hdl.handle.net/10398/9497.

Bordo, M. and A. Levin (2017). Central bank digital currency and the future of monetary policy. *NBER Working Paper Series 23711*. https://doi.org/10.3386/w23711.

Borgonovo, E., S. Caselli, A. Cillo, D. Masciandaro, and G. Rabitti (2021). Money, privacy, anonymity: What do experiments tell us? *Journal of Financial Stability 56*, 100934. https://doi.org/10.1016/j.jfs.2021.100934.

Brunnermeier, M. K. and D. Niepelt (2019). On the equivalence of private and public money. *Journal of Monetary Economics 106*, 27–41. https://doi.org/10.1016/j.jmoneco.2019.07.004.

Burlon, L., M. Muñoz, and F. Smets (2022). The optimal quantity of CBDC in a bank-based economy. *American Economic Journal: Macroeconomics (Forthcoming)*.

Calvo, G. A. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics 12*(3), 383–398. https://doi.org/10.1016/0304-3932(83)90060-0.

Davoodalhosseini, S. M. (2022). Central bank digital currency and monetary policy. *Journal of Economic Dynamics and Control 142*, 104150. https://doi.org/10.1016/j.jedc.2021.104150.

Debortoli, D. and J. Galí (2018). Monetary policy with heterogeneous agents: Insight from TANK models. *Universitat Pompeu Fabra Economics Working Paper Series No. 1686*. http://hdl.handle.net/10230/44714.

Deutsche Bundesbank (2021a). Payment behaviour in germany 2021. https://www.bundesbank.de/resource/blob/894118/6c67bcce826d5ab16a837bbea31a1aa9/mL/zahlungsverhalten-in-deutschland-2021-data.pdf. [Online; accessed 28 February 2023].

Deutsche Bundesbank (2021b). What do households in Germany think about the digital euro? First results from surveys and interviews. *Monthly Report October 2021*, 65–84. https://www.bundesbank.de/en/publications/reports/monthly-reports/monthly-report-october-2021-878746.

Dombrovskis, V. and F. Panetta (2023). Why Europe needs a digital euro. ECB Blog Post. https://www.ecb.europa.eu/press/blog/date/2023/html/ecb.blog230628~140c43d2f3.en.html. [Online; accessed 10 July 2023].

Engert, W. and B. S. C. Fung (2017). Central bank digital currency: Motivations and implications. *Bank of Canada Staff Discussion Paper 2017-16*. https://doi.org/10.34989/sdp-2017-16.

European Central Bank (2022). Study on the payment attitudes of consumers in the euro area (SPACE) – 2022. https://www.ecb.europa.eu/stats/ecb_surveys/space/shared/pdf/ecb.spacereport202212~783ffdf46e.en.pdf. [Online; accessed 14 August 2023].

European Central Bank (2023). Progress on the investigation phase of a digital euro – fourth report. https://www.ecb.europa.eu/paym/digital_euro/investigation/governance/shared/files/ecb.degov230713-fourth-progress-report-digital-euro-investigation-phase.en.pdf?704b0eee4c20eee4dbe4970f5091a96a. [Online; accessed 26 July 2023].

Fegatelli, P. (2022). A central bank digital currency in a heterogeneous monetary union: Managing the effects on the bank lending channel. *Journal of Macroeconomics 71*, 103392. https://doi.org/10.1016/j.jmacro.2021.103392.

Fernández-Villaverde, J., D. Sanches, L. Schilling, and H. Uhlig (2021). Central bank digital currency: Central banking for all? *Review of Economic Dynamics 41*, 225–242. https://doi.org/10.1016/j.red.2020.12.004.

Ferrari Minesso, M., A. Mehl, and L. Stracca (2022). Central bank digital currency in an open economy. *Journal of Monetary Economics 127*, 54–68. https://doi.org/10.1016/j.jmoneco.2022.02.001.

Galí, J. (2015). *Monetary Policy, Inflation, and the Business Cycle* (2 ed.). Princeton University Press.

George, A., T. Xie, and J. D. A. Alba (2020). Central bank digital currency with adjustable interest rate in small open economies. https://doi.org/10.2139/ssrn.3605918.

Goodell, G., H. D. Al-Nakib, and T. Aste (2024). Retail central bank digital currency: Motivations, opportunities, and mistakes. https://doi.org/10.48550/arXiv.2403.07070.

Gross, J. and J. Schiller (2021). A model for central bank digital currencies: Implications for bank funding and monetary policy. *Beiträge zur Jahrestagung des Vereins für Socialpolitik 2021: Climate Economics*. http://hdl.handle.net/10419/242350.

Kaplan, G., B. Moll, and G. L. Violante (2018). Monetary policy according to HANK. *American Economic Review 108*(3), 697–743. https://doi.org/10.1257/aer.20160042.

Kaplan, G. and G. L. Violante (2018). Microeconomic heterogeneity and macroeconomic shocks. *Journal of Economic Perspectives 32*(3), 167–194. https://doi.org/10.1257/jep.32.3.167.

Keister, T. and C. Monnet (2022). Central bank digital currency: Stability and information. *Journal of Economic Dynamics and Control 142*, 104501. https://doi.org/10.1016/j.jedc.2022.104501.

Kumhof, M. and C. Noone (2021). Central bank digital currencies — design principles for financial stability. *Economic Analysis and Policy 71*, 553–572. https://doi.org/10.1016/j.eap.2021.06.012.

Kumhof, M., M. Pinchetti, P. Rungcharoenkitkul, and A. Sokol (2023). CBDC policies in open economies. https://dx.doi.org/10.2139/ssrn.4388834.

Li, J. (2023). Predicting the demand for central bank digital currency: A structural analysis with survey data. *Journal of Monetary Economics 134*, 73–85. https://doi.org/10.1016/j.jmoneco.2022.11.007.

Luu, H. N., C. P. Nguyen, and M. A. Nasir (2023). Implications of central bank digital currency for financial stability: Evidence from the global banking sector. *Journal of International Financial Markets, Institutions and Money 89*, 101864. https://doi.org/10.1016/j.intfin.2023.101864.

Mancini-Griffoli, T., M. S. Martinez Peria, I. Agur, A. Ari, J. Kiff, A. Popescu, and C. Rochon (2018). Casting light on central bank digital currencies. *IMF Staff Discussion Notes No. 2018/008*. https://doi.org/10.5089/9781484384572.006.

Meyer, J. and F. Teppa (2024). Consumers' payment preferences and banking digitalisation in the euro area. *ECB Working Paper Series No. 2915*. https://doi.org/10.2866/4294.

Mishra, B. and E. Prasad (2024). A simple model of a central bank digital currency. *Journal of Financial Stability 73*, 101282. https://doi.org/10.1016/j.jfs.2024.101282.

Muñoz, M. and O. Soons (2023). Public money as a store of value, heterogeneous beliefs, and banks: implications of CBDC. *ECB Working Paper Series No. 2801*. https://doi.org/10.2866/952376.

Panetta, F. (2022). The digital euro and the evolution of the financial system. Speech at the Committee on Economic and Monetary Affairs of the European Parliament, Brussels, 15 June 2022. https://www.ecb.europa.eu/press/key/date/2022/html/ecb.sp220615~0b859eb8bc.en.html. [Online; accessed 6 March 2023].

Roesl, G. and F. Seitz (2022). Central bank digital currency and cash in the euro area: Current developments and one specific proposal. *Credit and Capital Markets 55*(4), 523–551. https://doi.org/10.3790/ccm.55.4.523.

Uhlig, H. and T. Xie (2020). Parallel digital currencies and sticky prices. *NBER Working Paper Series 28300*. https://doi.org/10.3386/w28300.