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

Jana Anjali Magin† Ulrike Neyer‡ Daniel Stempel§

Abstract

Many central banks are discussing 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 within 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 binding limit on CBDC holdings can increase the shock absorption capabilities of an economy. If the limit is used as a monetary policy instrument, prices will be stabilized more effectively after shocks. However, a CBDC implies distributional effects across households.

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

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†Heinrich Heine University Düsseldorf, Department of Economics, Universitätsstraße 1, 40225 Düsseldorf, Germany, email: jana.magin@hhu.de.

‡Heinrich Heine University Düsseldorf, Department of Economics, Universitätsstraße 1, 40225 Düsseldorf, Germany, email: ulrike.neyer@hhu.de.

§Corresponding Author, Heinrich Heine University Düsseldorf, Department of Economics, Universitätsstraße 1, 40225 Düsseldorf, Germany, email: daniel.stempel@hhu.de.

1 Introduction

Central banks worldwide are considering and debating 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, such as reserves, are only available to financial institutions. The introduction of a Retail CBDC would, therefore, enable central banks to provide the broader public with access to a digital form of central bank money. At present, 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 increasingly 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 to offer an additional means of payment rather than 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 are willing 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) Imposing a binding maximum amount of CBDC each household is allowed to hold, i.e., introducing a CBDC in a constrained manner, can improve the shock absorption capability of the economy. (iii) Using the

[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 (December 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).

CBDC 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 has distributional effects across households.

We reach these conclusions by analyzing 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. The main advantage of using a CBDC, namely the facilitation of payment transactions, is modeled 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 incur transaction costs.[3]

These transaction costs are the main driver for our results. In the no-CBDC regime, households face transaction costs, meaning part of their income has to be used to cover these costs and cannot be used for 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 with 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 reduce

[3]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, or as the costs of safeguarding privacy when using a private payment service provider.

their conventional money holdings only. As a result, the CBDC constraint becomes less binding, and transaction costs per unit of consumption decrease. This dampens the effects of the shock on output and prices. If the central bank uses the CBDC limit as a monetary policy instrument, it will further relax the constraint, thereby amplifying the dampening effects. Naturally, the extent to which households benefit from the introduction and existence of a CBDC depends on their preference for CBDC holdings. Differences in preferences imply that holding limits on CBDC in the 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 transitioning 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 the 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 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 for 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. Most closely related is the work by Ferrari Minesso et al. (2022), who 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, thereby affecting optimal monetary policy in the two countries asymmetrically. In their model, households face a Hotelling linear city setup, where they aim to minimize the distance between the available payment instruments and their respective preferences. Payment instruments are explicitly included in the households' utility function. If their preferred mix of payment instruments deviates from their actual mix, they will incur a utility loss. As they consider two countries, they include one representative households from each, assuming identical preferences for payment instruments across countries. 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. In another related work, Agur et al. (2022) models households also to face a Hotelling linear city setup but with an absolute-value loss function in the utility function and a focus on network externalities.

We contribute to this first strand of the literature in several ways. While many papers study interest-bearing CBDC holdings (and thus also consider CBDC as a store of value) that cannot be limited by the central bank, we take a more realistic approach. We consider a CBDC that is non-interest-bearing and potentially limited in its holdings, as it is planned in the euro area, for example. In particular, we assume that a deviation of the actual mix of payment instruments from the preferred mix results in additional costs for households (see Footnote 3) implying that households have less of their income available for consumption expenditures. This allows us to explicitly consider the means of payment 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 the distributional effects of a CBDC. In particular, we specifically focus on the distributional effects of a CBDC when households differ in terms of income and preferences for payment instruments.

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 such as anonymity. Key contributions in this area are 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 establish an equivalence condition. Fernández-Villaverde et al. (2021) confirm these main equivalence results but also 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 contribute to this literature by analyzing distributional and business cycle effects when using 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).[4] We contribute to this strand of the literature by assessing the 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 states the model calibration and provides a steady state analysis of introducing different CBDC-regimes. Furthermore, 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-

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

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 or deposits, for instance) and CBDC. We distinguish only between conventional money and CBDC without considering the specific allocation of conventional money. This is sufficient for our analysis as we want to focus on the impact of the introduction of a CBDC on the payment behavior of a heterogeneous household sector – specifically, the extent to which households replace payments made with conventional money with those made using a CBDC – and the resulting distributional effects as well as the implications for business cycle dynamics. Not explicitly considering deposits as a means of payment (but rather distinguishing only between conventional money and CBDC) allows us to exclude a banking sector from our model, i.e., we do not address potential problems of a possible disintermediation.[5] We assume that each household wants to hold a specific mix of these two types of money. Denoting real conventional money holdings by $m_{C,t}^k$ 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

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

[5] There is an important and intense debate regarding potential disintermediation effects associated with the introduction of a CBDC. However, this issue lies beyond the scope of our paper. We deliberately abstract from including a banking sector to focus exclusively on the distributional implications of changes in household payment behavior as well as the impact on business cycle fluctuations following the introduction of a CBDC. Regarding the problems of a potential disintermediation, we refer to the respective literature (see Footnote 2.)

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_t^k will always be satisfied. The central bank adjusts total money supply to match 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.,

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

with $m_{CB,t}^{max}$ being the maximum amount of CBDC in real terms each household is allowed to hold.[6] We discuss our assumptions regarding the central bank's behavior in more detail in Section 2.3. 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.[7] A household's actual share of conventional money holdings in its total money holdings Γ_t^k is thus given by[8]

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

[6]Note that we assume that shocks (as well as the potential reaction of the central bank) are sufficiently small such that the constraint is not occasionally binding. Thus, households know that they either face a binding constraint at all times or that the constraint is not binding for all t.

[7]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.

[8]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.

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 (scaled) deviation of actual money holdings from the optimal mix[9]

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

with $\zeta_{C,t}^k$ being defined as the change of this deviation in household k's consumption and γ denoting a scaling factor that allows us to realistically calibrate transactions costs. 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. 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 or higher costs of safeguarding privacy are incurred. 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. 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. 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. Furthermore, Ferrari Minesso et al. (2022) assume the same functional form in a similar context. While

[9] A different specification determining transaction costs would not change our results as long as it exhibits certain characteristics. We address this in more detail throughout this section. We additionally show that our model results remain qualitatively unchanged to an alternative specification of ζ_t^k in Appendix B.

their approach includes preferences over payment options in the utility function, we relate it to households' consumption expenditures. The general intuition, however, is the same.

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. Thus, the specification of transaction costs does not make a (qualitative) difference for our results as long as transaction costs depend positively on the share of conventional money in overall money holdings. Any specification including this property implies constant transaction costs per unit of consumption in the unconstrained and the no-CBDC regimes and increasing transaction costs per unit of consumption in consumption when there is a binding CBDC constraint.

The first order conditions (FOCs) for a household's optimal mix of money holdings are[10]

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

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

[10] 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.

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 binding, the household's marginal benefits of CBDC holdings will be higher than those from holding conventional money, but balancing marginal benefits will not be 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

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

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

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 $t+1$.[11]

The shared bond market implies risk sharing in the form of

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

with $\phi^k \equiv \frac{U_{c,SS}^k}{U_{c,SS}^{-k}} \frac{\Phi_{SS}^k}{\Phi_{SS}^{-k}}$, 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

[11] 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).

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.

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 potentially has two monetary policy instruments at its disposal: the nominal interest rate and the maximum amount of CBDC each household is allowed to hold. 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.

Total money supply is denoted by m_t^S. We assume that the central bank always adjusts m_t^S to households' total demand for money. In reality, the central bank directly controls only the quantity of cash and CBDC while the quantity of deposits depends on the behavior of commercial banks. However, in our model, we do not differentiate between different types of conventional money. Instead, we aggregate them (see Section 2.1). In this context, the central bank could theoretically print cash to meet the total demand for money.[12] Therefore, the households' total demand is always satisfied, but potentially not in the preferred composition, as the central bank can set a maximum amount of real CBDC holdings, $m^{max}_{CB,t}$, each household is allowed to hold. This can be interpreted as a perfectly inflation-indexed maximum nominal amount of CBDC (which makes sense as CBDC is considered to be a pure means of payment). Naturally, the no-CBDC regime implies $m^{max}_{CB,t} = 0 \forall t$. Conversely, the unconstrained regime implies that the central bank always satisfies CBDC demand. The central bank's behavior with respect to this constraint is therefore only relevant in the constrained regime and the monetary policy regime. It is captured by

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

where $m^{max}_{CB,SS}$ is the maximum amount of CBDC holdings in the steady state, and $\phi_{\pi,m}$ is the reaction coefficient of the central bank to inflation. In the constrained CBDC regime, $\phi_{\pi,m} = 0$, i.e., the amount of CBDC each household is allowed to hold is exogenously set by the central bank. In the monetary policy regime, $\phi_{\pi,m} > 0$, i.e., the central bank adjusts the real limit.[13] For instance, when the central bank observes inflation, it decreases the real amount of CBDC each household is allowed to hold.[14] 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 the steady state).

Note that we do not explicitly model the impact of introducing a CBDC on the central bank's balance sheet. Clearly, the introduction of a CBDC adds an additional item to the liabilities side. This could result in a simple exchange of liabilities by reducing cash

[12]Furthermore, it is important to note that, in reality, the central bank exerts a significant influence on the volume of deposits created through bank lending by setting short-term interest rates.

[13]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.

[14]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 in 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".)

and/or excess bank reserves, or in an expansion of the balance sheet through increased loans to commercial banks and/or higher holdings of securities on the asset side of the central bank's balance sheet.[15] This exchange of liabilities or balance sheet expansion may result in central bank losses or profits. This aspect could be incorporated into our model by including the respective positive or negative seigniorage in the households' budget constraint. Consequently, the introduction of a CBDC might constitute additional utility or disutility for households, as well as further distributional and business cycle effects. We disregard these potential seigniorage effects and focus only on the distributional and business cycle effects resulting from changes in households' payment behavior due to the introduction of a CBDC. However, relevant analyses addressing seigniorage can be found in Bindseil et al. (2024).

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

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

[15] Analyses regarding CBDC and the role of the central bank's operational framework, see, for example, Abad et al. (2024), Bindseil et al. (2024), and Fraschini et al. (2024).

In particular, demand for conventional money is always satisfied. Denoting the supply of conventional money as $m^S_{C,t}$, the market clearing condition is given by

$$m^S_{C,t} = m^k_{C,t}. \tag{36}$$

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:

$$m^S_{CB,t} = \begin{cases} m^k_{CB,t} & \text{if} \quad m^k_{CB,t} \leq m^{max}_{CB,t}, \\ \\ m^{max}_{CB,t} & \text{if} \quad m^k_{CB,t} > m^{max}_{CB,t}, \end{cases} \tag{37}$$

where $m^S_{CB,t}$ dentes the supply of CBDC.

3 Model Analysis

3.1 Calibration

Table 1 depicts the model calibration. In order to receive an appropriate level of income (and, thereby, consumption) inequality across households, a realistic constraint on CBDC holdings, preferences for conventional money or CBDC, and transaction costs, we identify and target relevant moments in the data. In particular, we utilize Eurostat data on the "mean consumption expenditure by income quintile" to identify the share of households potentially affected by a CBDC constraint of 3000 euros, a value currently contemplated by the ECB (Panetta, 2022). Considering an average weight of 0.5 on both conventional money and CBDC in overall money holdings as in Ferrari Minesso et al. (2022), the two highest income quintiles could potentially face a binding CBDC constraint considering their consumption expenditures.[16] Thus, we set κ to 0.4. We then calibrate α to match the relative consumption expenditure of households H and L, with high-income households spending 56% more on consumption than low-income households. We incorporate the fact that households with higher income exhibit higher preferences for digital payment options

[16] See Appendix A for details.

by setting $\omega_L > \omega_H$. Meyer and Teppa (2024) show that higher income quintiles prefer digital means of payments by roughly 10 percentage points (pp), depending on the type of digital payment option. Li (2023) shows that the differences in CBDC demand could be much larger across income groups, depending on the specific CBDC design. We consider a 10 pp gap between household H and L to ensure that our results constitute a lower bound.[17] The weighted average preference for CBDC is set to 0.5 as in Ferrari Minesso et al. (2022), yielding $\omega_L = 0.54$ and $\omega_H = 0.44$. Based on these preferences and the households' average consumption expenditures, we can set a value for the CBDC constraint that is equivalent to a 3000-euro limit.[18] Finally, we calibrate the value of γ to receive an empirically plausible value for transactions costs. Following Krüger and Seitz (2014) who show that the overall transaction costs for different types of payment methods amount to values around 1% of GDP for European countries, the value of γ is calibrated in a way that transaction costs amount to 1% of GDP in the model when there is no CBDC available.[19]

The remaining parameters are set as follows. As Ferrari Minesso et al. (2022) we set the elasticity of substitution between good varieties to 6 and the elasticity of substitution between conventional money and CBDC to 0.5.[20] We further choose the habit parameter and the inverse Frisch elasticity of labor supply to values that are realistic for European countries (see Albonico et al., 2019). 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 level of price stickiness, and the central bank's reaction coefficient of inflation are chosen as in Galí (2015).

[17] We consider a larger difference of household preferences for CBDC when discussing the relevance of household heterogeneity in Section 3.4.

[18] We discuss the relevance of the holding limit's value in Section 3.5.

[19] Note that we interpret the transaction costs in our model in a broader sense (transactions not undertaken by a household due to the unavailability of the preferred payment option, for instance) than the ones in Krüger and Seitz (2014). Thus, these costs constitute a lower bound.

[20] Assenmacher et al. (2021) use a value of 2 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 C.

Table 1: Calibration.

	Description	Value	Target/Source
		Households	
κ	Share of H-households	0.4	Eurostat
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	0.995	Annual interest rate: 2%
ω_H	Weight on conventional money H	0.44	Ferrari Minesso et al. (2022), Meyer and Teppa (2024), calibrated
ω_L	Weight on conventional money L	0.54	Ferrari Minesso et al. (2022), Meyer and Teppa (2024), calibrated
φ_k	Elasticity of substitution between conventional money and CBDC	0.5	Ferrari Minesso et al. (2022)
γ	Transaction cost parameter	0.074	Krüger and Seitz (2014), calibrated
		Firms	
α	Productivity household H	0.647	Eurostat, calibrated
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	20	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.[21] 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. Note that despite the higher consumption per hour of work, households have no incentive to change their labor supply. The introduction of a CBDC in an unconstrained manner reduces ζ to zero, i.e., total output is consumed. Consider equation (15): 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.[22] As both households can realize their preferred mix of money holdings, no transaction costs

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

[22]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 $\chi N^{\eta} = \frac{W}{P}\frac{1}{C(1+\zeta)} = \frac{W}{P}\frac{1}{Y}$. See also footnote 24.

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 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.[23] The calibrated CBDC limit corresponds to roughly three quarters of the households preferred level of CBDC holdings (an equivalent of 3000 euros).

Table 2: Steady State Comparison.

		Relative Steady State Value		
Variable	Description	No CBDC	CBDC constr.	CBDC unconstr.
C_{SS}^{L}	Consumption L	1	1.006	1.008
C_{SS}^{H}	Consumption H	1	1.007	1.012
$Y_{C,SS}$	Consumption-relevant output	1	1.007	1.010
Y_{SS}	Output	1	0.997	1
N_{SS}^{L}	Labor L	1	1	1
N_{SS}^{H}	Labor H	1	0.996	1
$m_{C,SS}^{L}$	Conventional money holdings L	1	0.539	0.540
$m_{C,SS}^{H}$	Conventional money holdings H	1	0.727	0.440
$m_{CB,SS}^{L}$	CBDC holdings L	–	1	1.002
$m_{CB,SS}^{H}$	CBDC holdings H	–	1	1.316
U_{SS}^{L}	Utility L	1	1.001	1.001
U_{SS}^{H}	Utility H	1	1.001	1.002

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 in the constrained regime household H 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 H ac-

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

tually works less as the introduction of a binding constraint on CBDC holdings causes marginal disutility of work to be higher than marginal utility.[24] This behavior allows it to reduce its transaction costs per unit of consumption, i.e., to use a higher share of its income for 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 consumption. In the other regimes this possibility does not exist.[25]

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. At the same time, the decrease in transaction costs has similar effects on household L as it does on household H. Thus, unlike household H, household L faces two opposing effects on its consumption. In our calibration, the positive effect outweighs the negative one, leading household L to also increase consumption. It is notable, however, that for other reasonable calibrations (particularly ones that include larger transaction costs), the net effect on household L's consumption (and utility) could become negative. Household L's consumption would be partly crowded out by household H's consumption in that case. Generally, the introduction of CBDC implies distributional effects as household H benefits more from its introduction than household L. 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

[24]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 22), 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 22). However, if there is a binding constraint, the term is strictly smaller than 1.

[25]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.

decreases and the central bank reacts by decreasing the nominal interest rate to incentivize consumption and mitigate the effects of the shock.

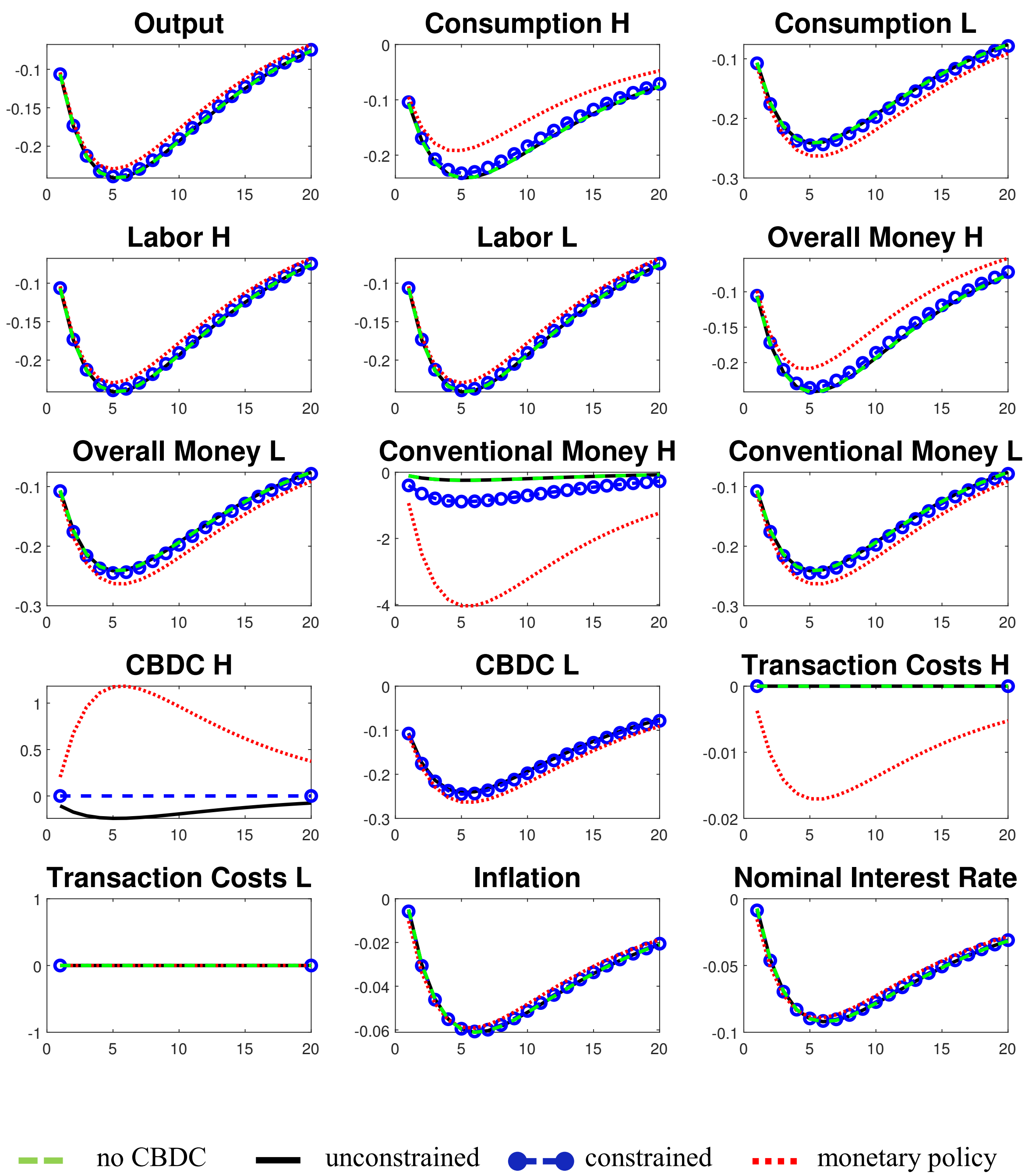

Figure 1: Impulse Responses to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$.

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. For our particular calibration, output and inflation decrease by up to 2% less in the constrained regime and up to 11.5% in the monetary policy regime. 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 the effects are 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 regime with the ones of the unconstrained/no-CBDC regime, we find that consumption of household H decreases less in the constrained 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 regime.

In the monetary policy regime, the central bank is able to stabilize inflation by adjusting the CBDC limit. The inflation rate increases by up to 10% less in comparison to the unconstrained/no-CBDC regime for our calibration. The central bank reacts to the increase in inflation by decreasing the maximum amount of CBDC to further reduce consumption. The constraint thus becomes more restrictive but only for household H. Household H therefore holds even less CBDC than it wishes to hold and increases its conventional money holdings in return. Transaction costs per unit of consumption increase. As a result, household H's consumption decreases more than in the other three regimes, while household L's consumption decreases less. Overall, inflation increases less than in the other regimes. However, output decreases even more as the central bank reduces the amount of CBDC (and therefore negatively affects consumption). Monetary policy thus has a stronger impact on inflation. However, this also amplifies the negative effects on output. In addition, using CBDC as a monetary policy instrument implies distributional effects: the decrease in household H's consumption and the corresponding lower increase in prices leads household L to decrease its consumption less strongly.

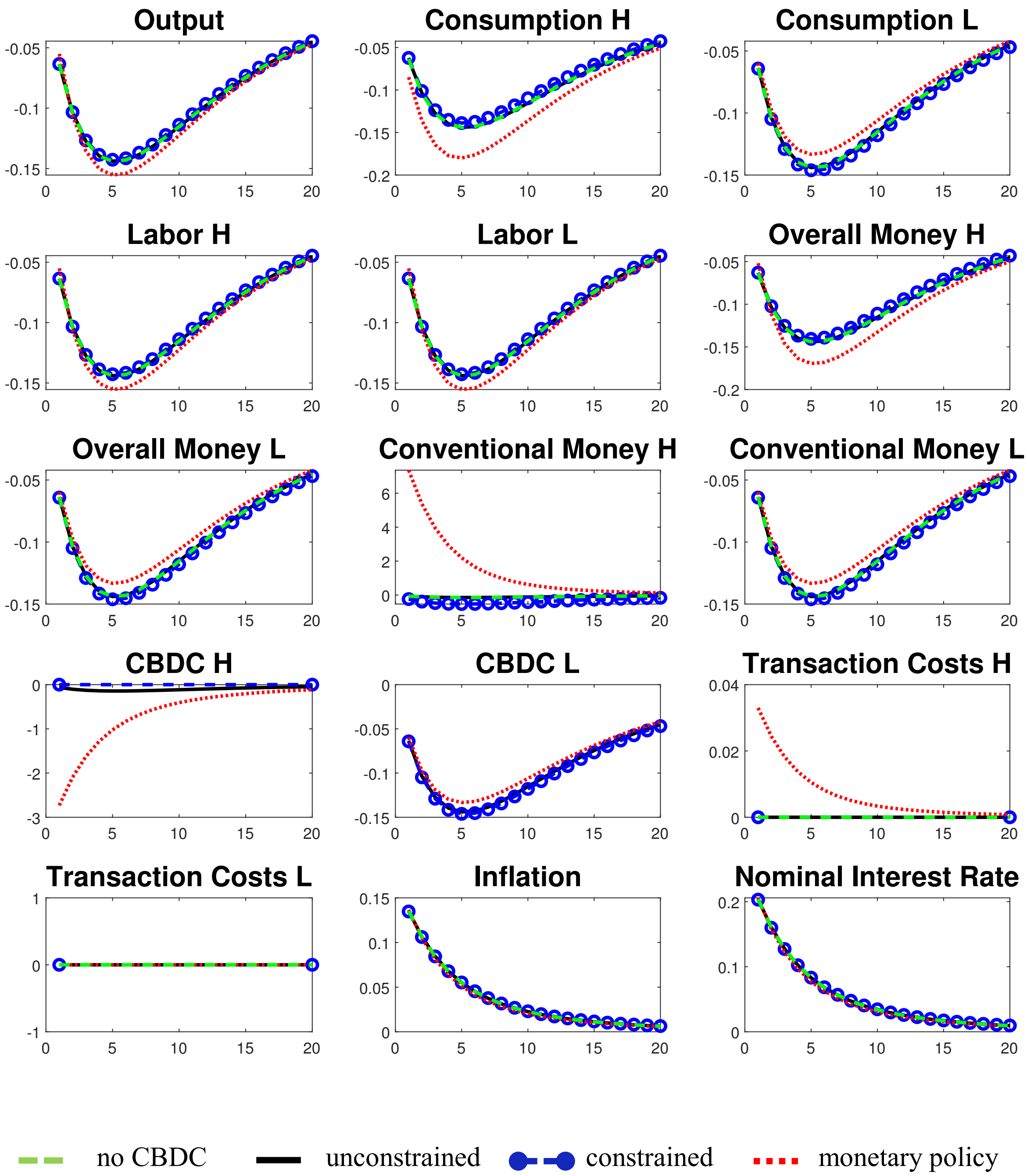

Figure 2: Impulse Responses to a 1% Cost-Push Shock (A_t^k) with Persistence $\rho_A = 0.9$.

3.4 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 difference between the preferences of households H and L for holding CBDC. In particular, we decrease ω^H from 0.44 (baseline calibration) to 0.4 while increasing ω^L from 0.54 to 0.567, thereby keeping the (weighted) average preference for conventional money/CBDC constant at 0.5.

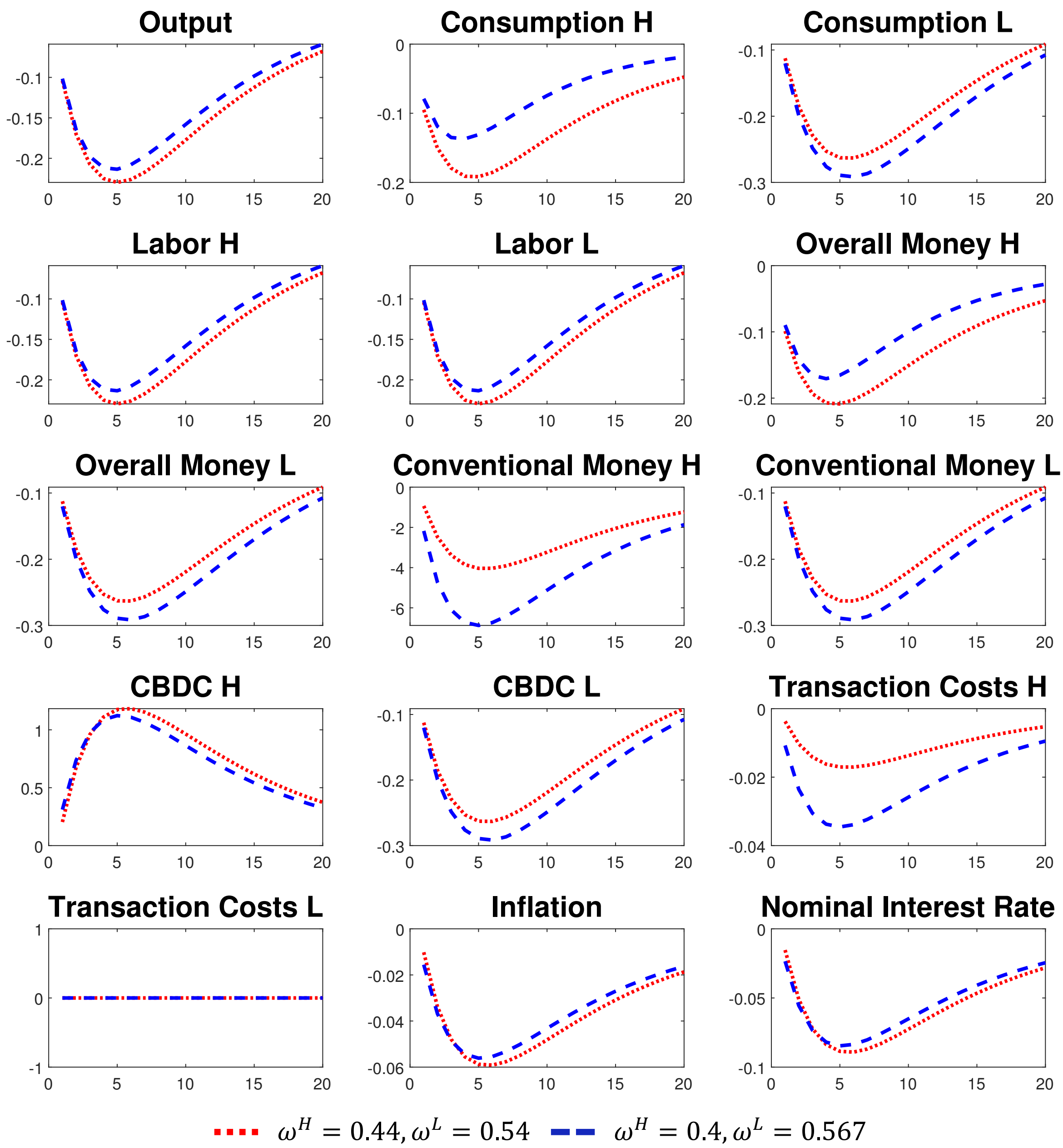

Figure 3: Impulse Responses in the Monetary Policy Regime to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$ for Different CBDC Preferences.

This implies that the CBDC constraint becomes more binding for H. Thus, the discussed effects of the CBDC limit in the constrained and the monetary policy regime are amplified. 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^k under the monetary policy regime in detail to provide some intuition for this result.

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 the difference in CBDC preferences is high. Simultaneously, distributional 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. 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 distributional 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 the preference for CBDC of the constrained household is larger. 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., $\omega^k = 0.5$. In this case, the constraint is still (not) binding for household H (L) but to a lesser extent. Thus, the effects of using the CBDC limit as a monetary policy instrument are mitigated in comparison to the baseline calibration. The intuition behind this result is the same as outline above (in the opposite direction). The impulse responses are displayed in Appendix D.

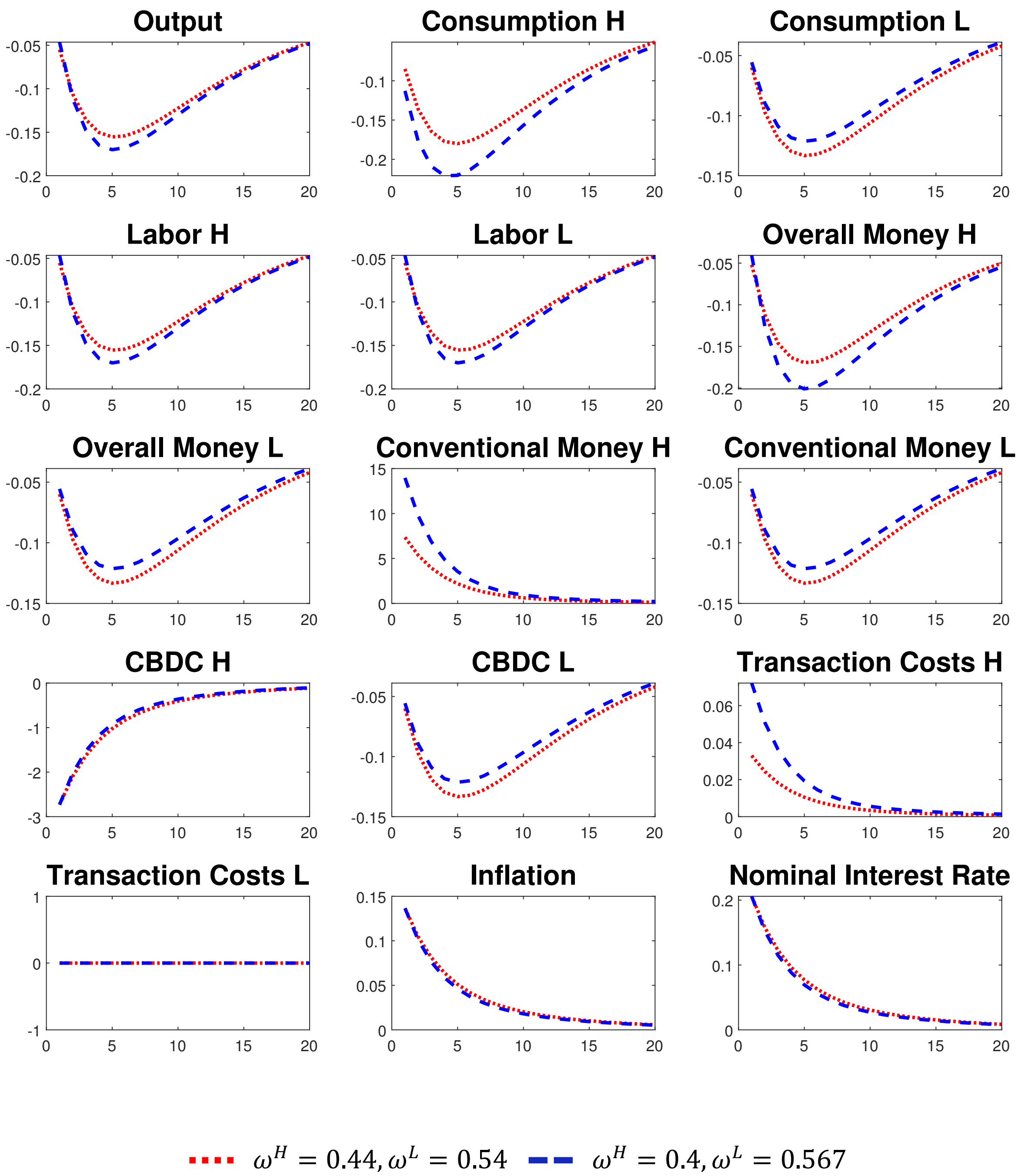

Figure 4: Impulse Responses in the Monetary Policy Regime to a 1% Cost-Push Shock (A_t^k) with Persistence $\rho_A = 0.9$ for Different CBDC Preferences.

3.5 The Relevance of the Amount of the CBDC Limit

Next we discuss the relevance of the chosen CBDC limit for our results. While our baseline calibration includes the equivalent of the 3000-euro limit contemplated by the ECB, an interesting exercise is the comparison of the model responses to shocks for different amounts of this (not yet fixed) limit. For instance, if the amount of CBDC available to households were so large that it did not constitute a binding constraint to any household, the economy would, naturally, effectively move towards the unconstrained case. More interestingly, the central bank could decide to introduce a lower constraint. We simulate the model responses including an equivalent of a 2500-euro limit. The responses to a demand and a cost-push shock under the monetary policy regime are shown in Figures 5 and 6, respectively.

Generally, a lower limit implies that the constraint is more binding for household H. This again implies that the effects of the CBDC limit in the constrained as well as in the monetary policy regime are amplified when considering a (more binding) 2500-euro limit instead of 3000-euro limit. The same intuition as in Section 3.4 applies.

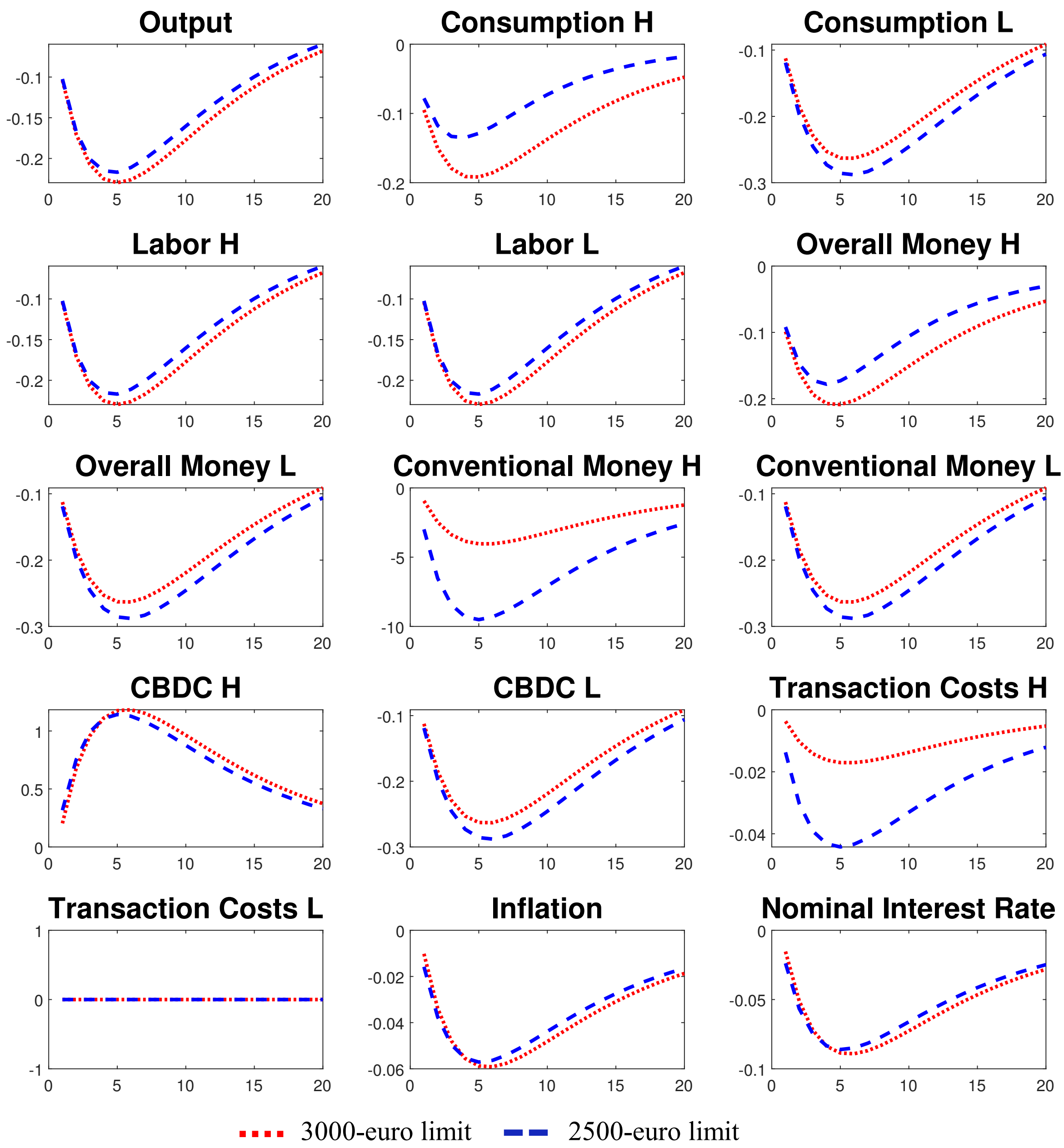

Figure 5: Impulse Responses in the Monetary Policy Regime to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$ for Different CBDC Limits.

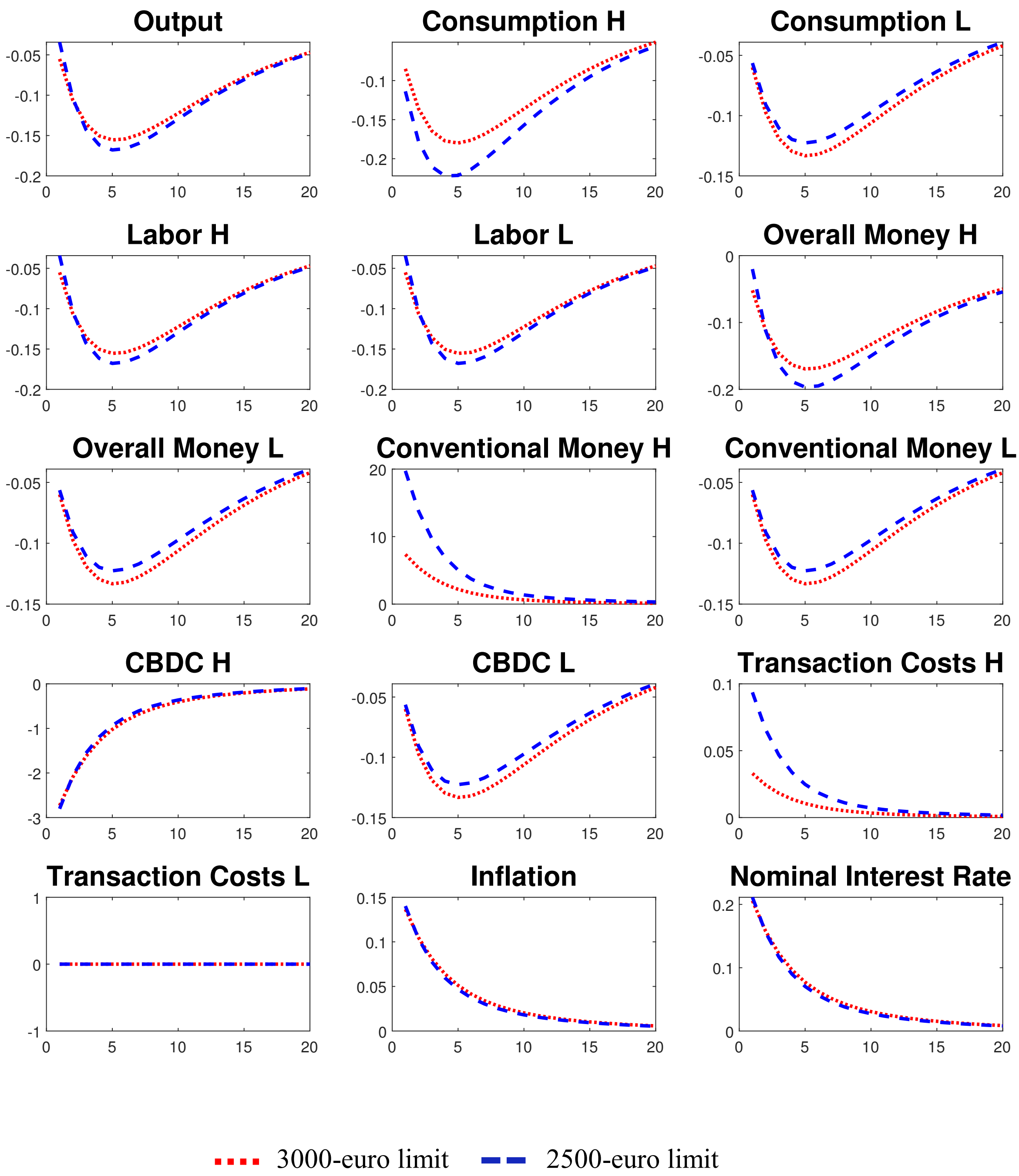

Figure 6: Impulse Responses in the Monetary Policy Regime to a 1% Cost-Push Shock (A_t^k) with Persistence $\rho_A = 0.9$ for Different CBDC Limits.

4 Conclusion

Over the past years, there has been an ongoing debate about advantages and disadvantages of introducing a CBDC, including questions about whether and how central banks should issue it. Additionally, households differ in their demand for a CBDC depending on their income. Against this background, we investigate the distributional and business cycle 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 for holding 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 in a constrained manner increases the economy's ability to absorb demand shocks. Both output and prices deviate less from their steady states after the shock. Following cost shocks, output deviations are similarly reduced, but prices deviate further from their steady state. The main driver of these results are transaction costs. The introduction of a CBDC lowers the transaction costs per unit of consumption. In the two regimes with a binding limit on CBDC holdings, transaction costs per unit of consumption increase with consumption, which explains the change in the economy's 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. Note that these results are driven primarily by the presence of a binding constraint on CBDC holdings rather than household heterogeneity. The results would be quantitatively even stronger if the constraint were binding for both households. However, considering household heterogeneity allows us to show that introducing a CBDC, as well as using the CBDC limit as a monetary policy instrument, has distributional effects across households.

Our primary focus is on the distributional and business cycle effects arising from changes in household payment behavior due to the introduction of a new means of payment, namely CBDC. Therefore, we do not include a banking sector in our model. While this allows us to concentrate on our primary objectives, it does come with the drawback of not accounting for potential disintermediation effects or other monetary transmission mechanisms. However, to address the extensive ongoing discussion of these issues we refer to the relevant literature (see references mentioned in Footnote 2).

Our findings also raise important questions regarding the implementation of monetary policy using a CBDC limit as a policy instrument. Similar to other monetary policy instruments or the considerations on interest-bearing CBDC, the use of the CBDC holding limit as a monetary policy instrument involves drawbacks: An additional monetary policy instrument introduces a further source of uncertainty regarding monetary policy. This issue also poses an additional challenge for central bank communication. Furthermore, as revealed by our model, using the CBDC limit as a monetary policy tool also entails distributional effects. This is particularly relevant as we consider an inflation-indexed limit in our model. In practice, this implies that a central bank setting a nominal CBDC limit – thereby allowing the real limit fluctuate with inflation – would operate within the monetary policy regime of our model. Consequently, setting a (nominal) 3000-euro limit, as contemplated by the ECB, would imply additional distributional effects.

Finally, there are several interesting paths for future research. Analyzing the implications of even more alternative CBDC regimes in an economy with heterogeneous households, as well as extending our framework to analyze a heterogeneous monetary union model seem to be interesting for future research. Another relevant avenue is the consideration of financial inclusion aspects in a model with household heterogeneity, as this might imply distributional effects of a CBDC that specifically benefit households with lower income.

A Consumption Expenditure Data

We utilize consumption expenditure date to identify the share of households that might be affected by a 3000-euro CBDC limit. The latest Eurostat data on "mean consumption expenditure by income quintile" is available for 2020. As the data is not available for the euro area, we utilize the consumption data for Germany as the largest euro area economy. The consumption expenditures by income quintile can be found in Table A.1. We convert annual expenditures into quarterly expenditures. Considering a 3000-euro limit as well as an average preference of 0.5 for CBDC, the constraint could potentially be binding for quintiles 4 and 5. The third row then reports the average quarterly consumption expenditures of income quintiles 1, 2, and 3 as well as quintiles 4 and 5, respectively.

Table A.1: Consumption Expenditures by Income Quintile in Germany.

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
Annual	13,305	18,504	22,162	25,030	31,368
Quarterly	3,326	4,626	5,541	6,258	7,482
Average quarterly			4,498		7,050

Notes. Source: Eurostat. Values in euros. Average quarterly refers to the average consumption expenditures by income quintiles 1, 2, and 3 as well as quintiles 4 and 5, respectively.

B Alternative Specification of Transaction Costs

We check the robustness of our results derived in Section 3.3 with respect to the specification of transaction costs, in particular of ζ_t^k (equation (11)). Apart from this, we assume the household behavior to remain unchanged. We consider the following definition

$$\zeta_t^k = \frac{\gamma}{2} \left(\Gamma_t^k \right)^2 , \tag{B.1}$$

i.e., households generally face transaction costs when using conventional money. This specification implies that the criteria discussed in Section 2.1 are met: transaction costs per unit of consumption are constant in the unconstrained and no-CBDC cases, and increase in consumption when the constraint is binding. The parameter γ is calibrated in the same way as in the baseline calibration. As households now incur transaction costs whenever they hold conventional money, γ is lower (0.02). Figures B.1 and B.2 show the results for a demand and a cost-push shock, respectively. We find that our results remain qualitatively unchanged. Intuitively, the effects of the constraint itself as well as the effectiveness of using it as a monetary policy tool decreases when γ is lower.

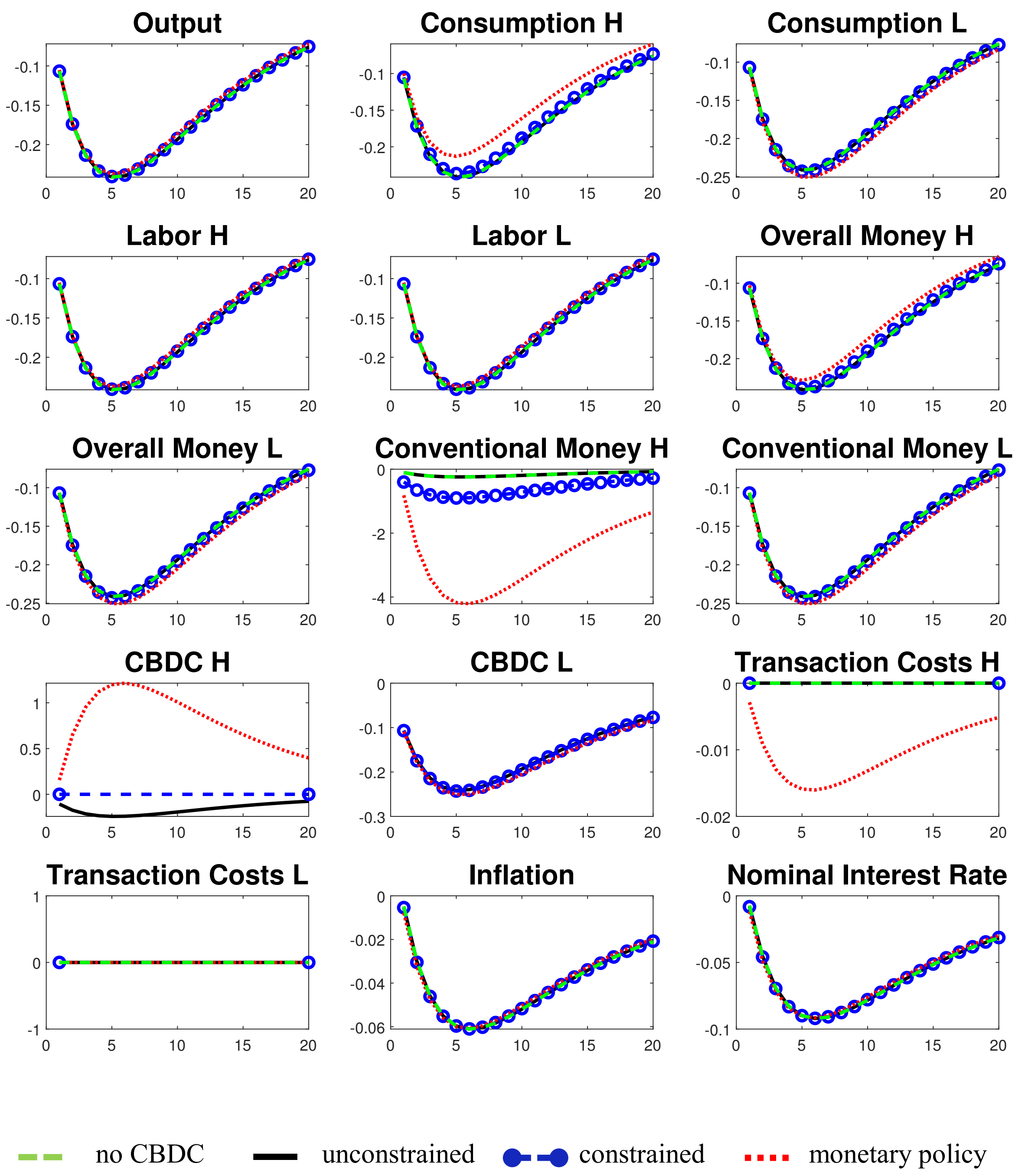

Figure B.1: Impulse Responses to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$ and Alternative Specification of ζ_t^k.

The stabilizing effect on output and inflation after a demand shock decreases to about 1% (from 2% in the baseline) in the constrained and to roughly 5.75% (from 11.5%) in the monetary policy regime. The inflation-stabilizing effect of the monetary policy reime following the cost-push shock decreases to 3% (from 10%).

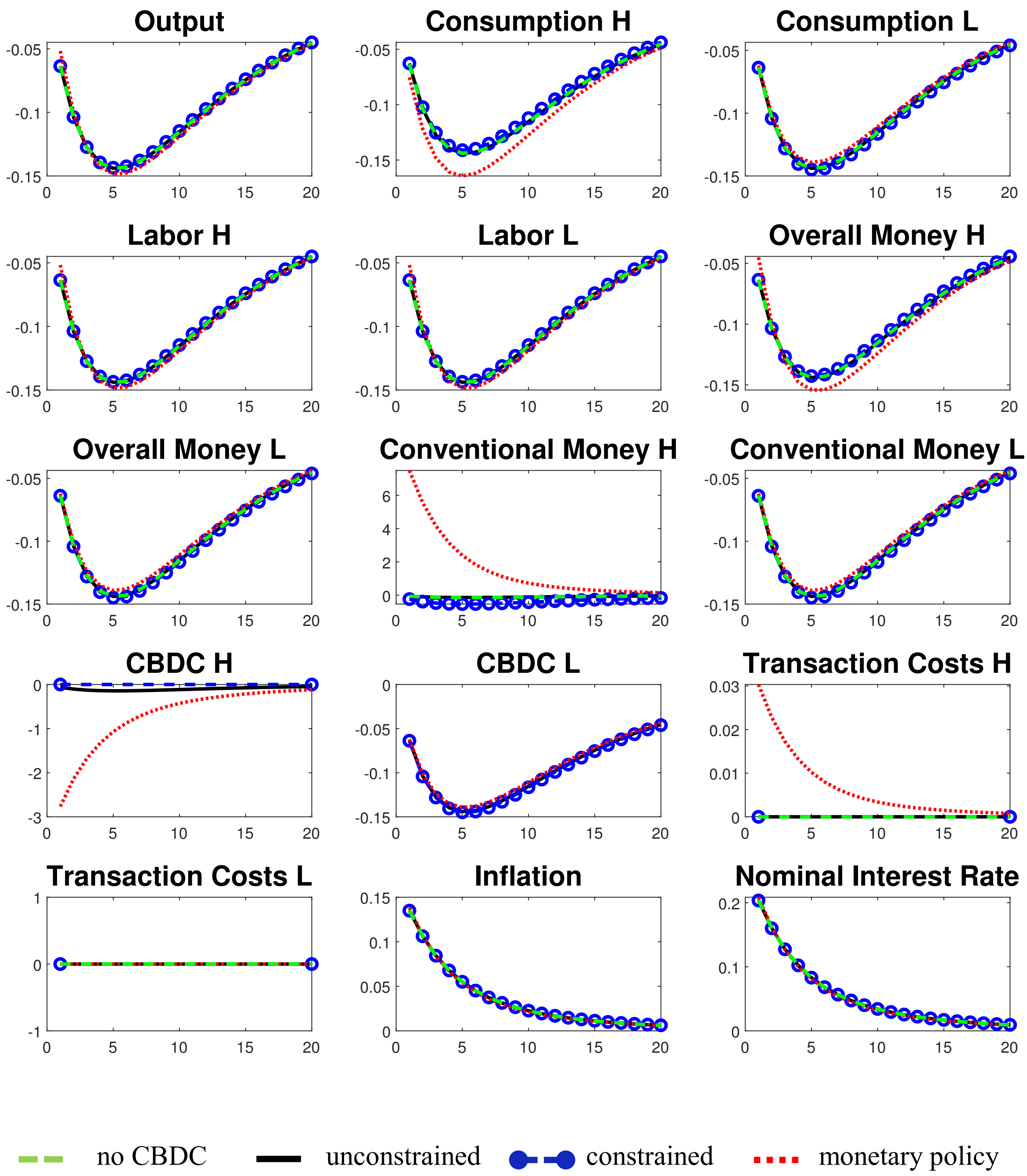

Figure B.2: Impulse Responses to a 1% Cost-Push Shock (A_t^k) with Persistence $\rho_A = 0.9$ and Alternative Specification of ζ_t^k.

C 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.

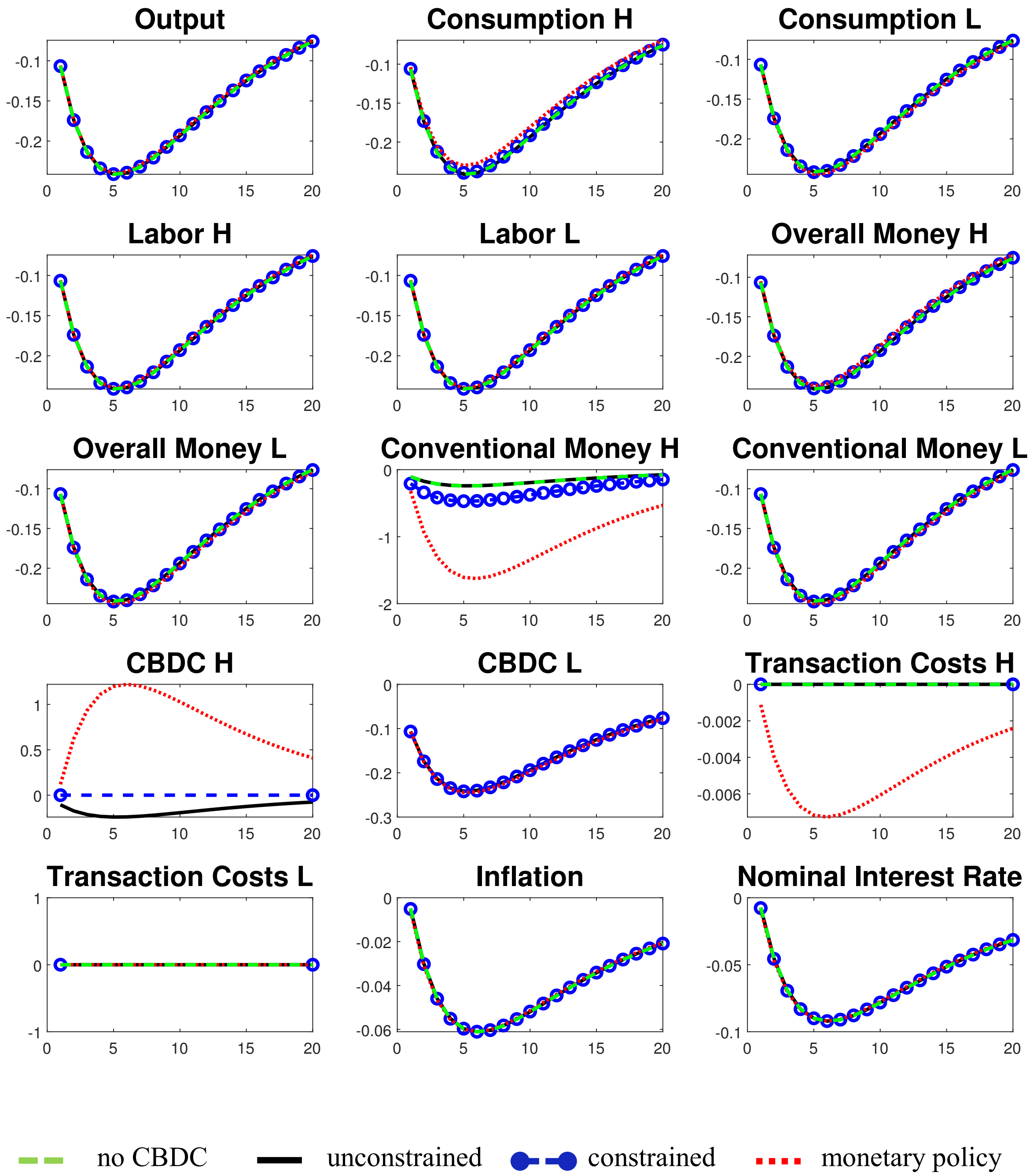

Figure C.1: Impulse Responses to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$ and Elasticity of Substitution Between Conventional Money and CBDC $\varphi_k = 2$.

While we set the elasticity of substitution to 0.5 in our baseline calibration, implying a relatively low degree of substitutability, our results remain qualitatively unchanged when considering a higher elasticity of substitution ($\varphi_k = 2$) as shown in Figures C.1 and C.2.

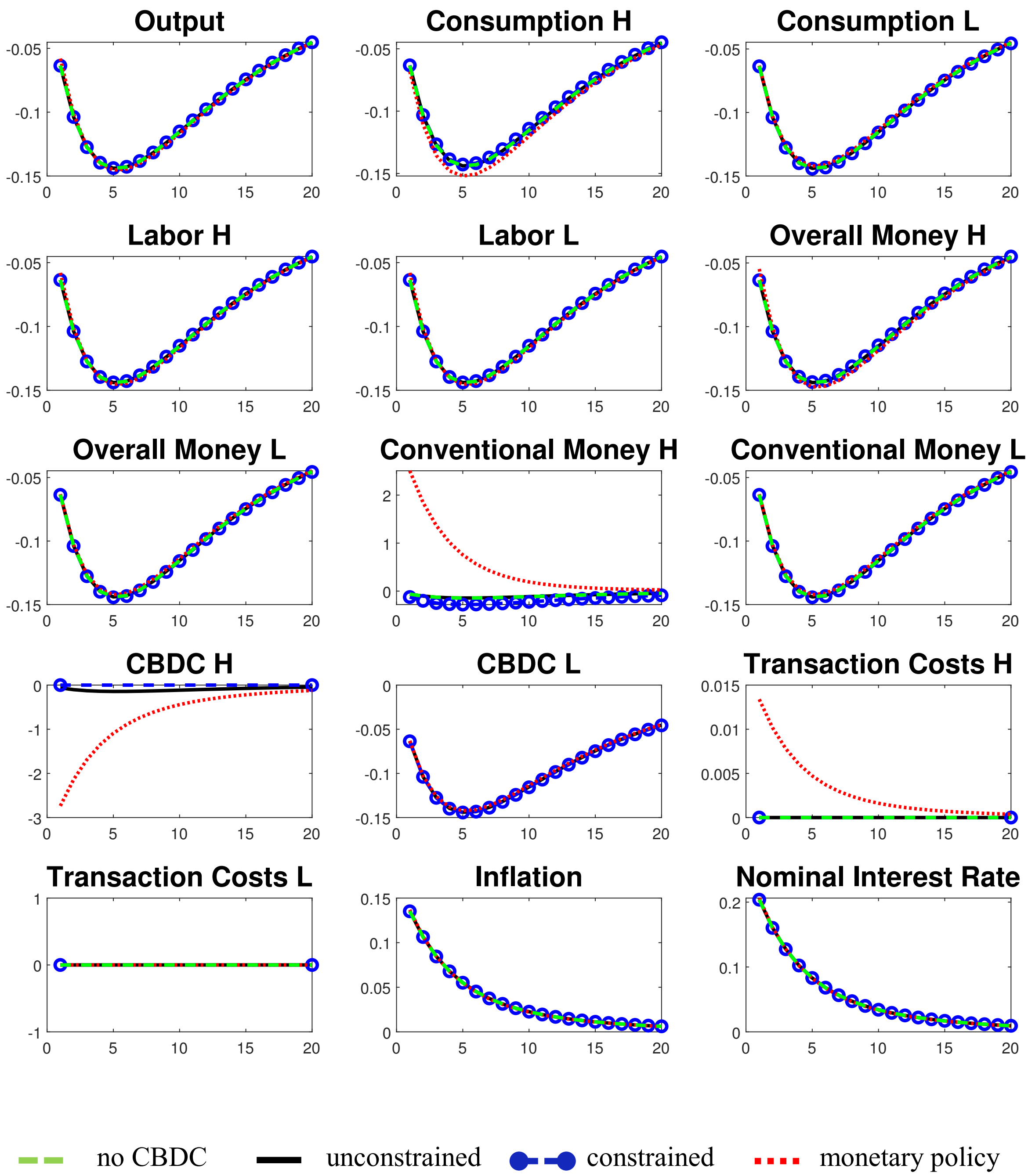

Figure C.2: Impulse Responses to a 1% Cost-Push Shock (A_t^k) with Persistence $\rho_A = 0.9$ and Elasticity of Substitution Between Conventional Money and CBDC $\varphi_k = 2$.

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. In particular, the stabilizing effect on output and inflation of a CBDC in the constrained regime after a demand shock decreases to 0.35% (from 2% in the baseline) and to 2.2% (from 11.5%) in the monetary policy regime. After the cost-push shock, the inflation-stabilizing effect in the monetary policy regime decreases to 1.9% (from 10%).

D Equal CBDC Preferences

Equal preferences across households for conventional money and CBDC implies that the constraint still does not bind for household L but becomes less binding for household H. Thus, the (potentially stabilizing) effects of the CBDC constraint are lower after both shocks. Figures D.1 and D.2 demonstrate this for the monetary policy regime under the baseline calibration as well as for equal CBDC preferences across households after a demand and a cost-push shock, respectively.

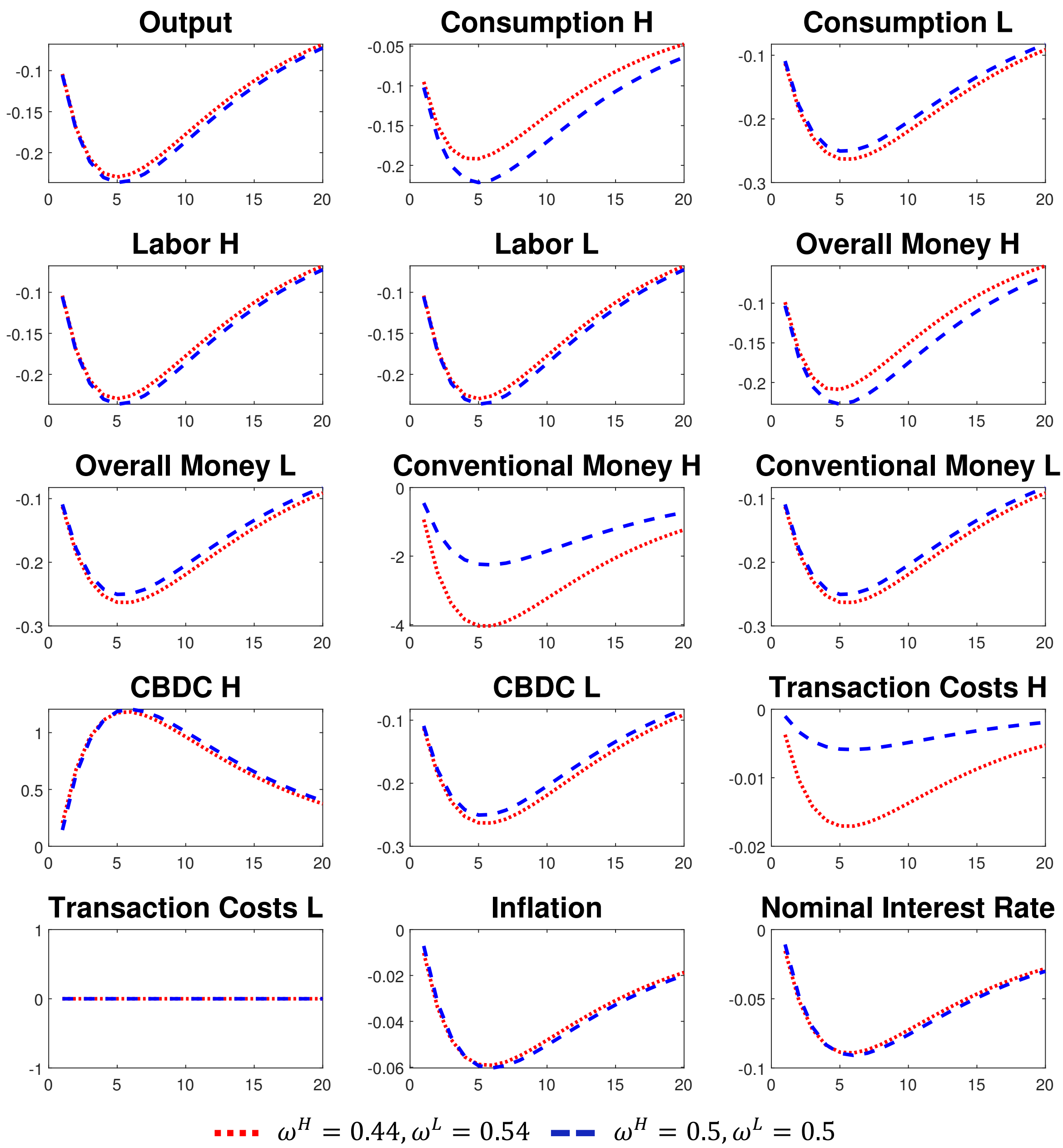

Figure D.1: Impulse Responses in the Monetary Policy Regime to a Negative 1% Demand Shock (Z_t^k) with Persistence $\rho_Z = 0.9$ for Different CBDC Preferences.

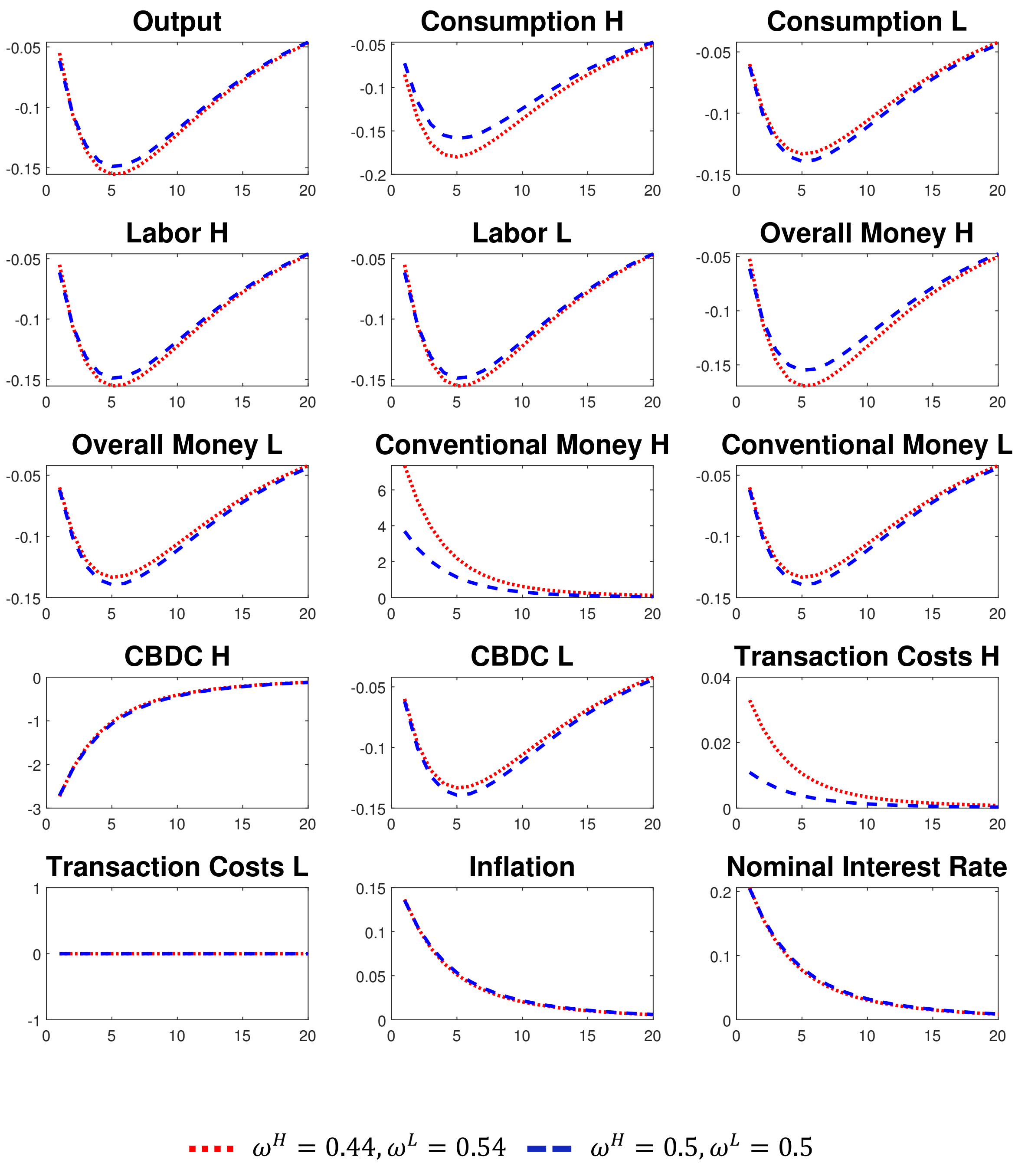

Figure D.2: Impulse Responses in the Monetary Policy Regime to a 1% Cost-Push Shock (A_t^k) with Persistence $\rho_A = 0.9$ for Different CBDC Preferences.

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