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Macroeconomic modelling of CBDC: a critical review

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Abstract

Over the last decades, macro-economists have renewed their efforts to reduce the gap between monetary macroeconomics and real-world central banking. This paper reviews how macroeconomics has since 2016 approached the possible introduction of retail central bank digital currencies (CBDC). A review of the literature reveals that macroeconomic models of CBDC often rely on CBDC design features and narratives which are no longer in line with the one of central banks actually working on CBDC. In particular, the literature often (i) does not take into account the nature of central banks' CBDC issuance plans as a "conservative" reaction to profound technological and preferential shifts in the use of money as a means of payments, (ii) does not start from design features communicated by central banks, such as no-remuneration, quantity limits, access restrictions, and automated sweeping functionality linking CBDC wallets with commercial bank accounts; (iii) does not explain well enough the difference between CBDC and banknotes within their macro-economic models, apart from remuneration (which central banks actually do not foresee); and (iv) assume that CBDC will lead to a significant increase in the total holdings of central bank money in the economy, although (i) and (ii) make this unlikely.

JEL Classification: E3; E5; G1

Key Words: central bank digital currencies; macroeconomics; financial stability; central bank money

Non-technical summary

The digitalization of large parts of everyday life and of the economy also extends to payment transactions. In the euro area, for example, the share of cash payments at the point-of-sale (i.e. in physical shops) declined from 79% to 59% between 2016 and 2022, mainly for the benefit of card payments. If this trend continues or even accelerates, the role of cash and thus central bank money would decrease significantly for the benefit of private payment service providers. This also raises concerns about insufficient competition, inclusiveness, privacy protection as well as strategic autonomy of sovereign states.

Against this backdrop, a heated debate about retail digital money issued by central banks - central bank digital currency (CBDC) - began in 2016. Due to the growing number of papers that present macro-economic models examining CBDC and, on the other hand, quite detailed plans by central banks to issue CBDC, this paper examines to what extent the assumptions and scenarios contained in these macroeconomic models of CBDC correspond to the objectives and emerging design choices communicated by central banks and related to this, how applicable the papers' predictions of macroeconomic effects are to the CBDCs outlined or announced by central banks. The choices to be made with regards to the issuance and design of CBDC are of high importance for society, and central bankers and legislators want to understand what is at stake.

All central banks working on CBDC have announced that CBDC would not be remunerated, that holdings would be limited, and that CBDC issuance would aim to *preserve* the roles of central bank money in retail payments in a digitalized world. Another set of key features announced for CBDCs are those that allow to somewhat decouple the store of value from the means of payments function of CBDC and that facilitate the preservation of a single pool of money for citizens. For example, the ECB announced a so-called "reverse waterfall" so that users would not have to prefund a digital euro account before making payments because the digital euro account can be linked to a commercial bank account. Last but not least, central banks have announced access restrictions for CBDC. For example, the ECB plans to only allow natural persons who are permanent residents of the euro area (or possibly of the EU), and temporary residents (e.g. travelers) to be able to hold digital euro within the limits.

The features that central banks have announced are important for any macroeconomic consequences of CBDC. However, our paper finds that the macro-economic literature often provides answers to key policy questions which rely on early CBDC narratives and design assumptions, and less on the explanations and plans outlined by central banks. Our paper identifies in particular the following gaps which future research on the macroeconomics of CBDC could consider closing.

First, the modelling in all the papers assumes that the decision to issue CBDC hits a static monetary and financial system and is not a reaction of the central bank to a changing payments environment. According to recent central bank explanations, the decision to issue CBDC would however be a "conservative" response to profound changes of the monetary system relating to digitalization, notably the lesser and lesser use (and ultimately lower stock) of banknotes.

Second, many papers do not consider the design features of possible CBDCs as outlined more recently by central banks. Most papers assume remunerated CBDC, or that CBDC is of considerable volume, and derive macroeconomic effects from that, although at least since 2019 all ongoing central bank CBDC initiatives centered on non-interest-bearing CBDC.

Third, as real-world CBDCs are expected to be unremunerated, it is difficult to specify a clear difference between CBDC and cash in macro-economic models, and indeed none of the papers develops this difference in a way that could imply macro-economic consequences.

Fourth, and relating to previous points, the papers generally tend to assume, in line with earlier narratives, that the issuance of CBDC will considerably increase the amount of central bank money in circulation. The declining use of banknotes, and the very prudent CBDC design as announced for example by the ECB, make rather likely that the total amount of central bank money in circulation will follow a lower trend growth in the future than it did in the past. Moreover, the models who base their macroeconomic predictions on the assumed effect of CBDC to increase central bank money in circulation could be considered to not really be models of the effects of CBDC (but models describing the macroeconomic effects of a larger amount of central bank money in circulation, which could be driven equally well by an increase of banknotes).

Under the assumption of ever-progressing digitalization of society, the macro-economic effects of issuing CBDC should be identified starting from the counterfactual. If retail payments are exclusively left to the private sector and central bank money would be marginalized, then the amount of central bank money in circulation will significantly shrink, the length of central bank balance sheets would decline and the banks would benefit from deposit inflows, payment costs will increase (due to increasing market power of the successful firms in a market with strong network externalities), monetary and financial stability will be weakened (as the unifying convertibility test of all private moneys, i.e. to be exchangeable at sight against central bank money, will have become remote or inexistant), and strategic autonomy will be undermined with negative consequences under scenarios of a further geopolitical deterioration. In this sense, the issuance of CBDC aims at preserving economic efficiency and stability by preserving the current role of central bank money (a genuine public good).

Of course, it cannot be excluded that some central banks and legislators will in the future design CBDCs which better match the assumptions taken in the macro-models reviewed. For this reason, the models remain useful for future scenarios. Moreover, macro-economic researchers could review the macro-economic predictions of the models for CBDCs designed as in recent central bank communications.

1. Introduction

The digitalization of large parts of everyday life and of the economy also extends to payment transactions. In the euro area, for example, the share of cash payments at the point-of-sale (i.e. in physical shops) declined from 79% to 59% between 2016 and 2022, mainly for the benefit of card payments.[1] In the US, cash use fell from 40 percent in 2012 to 19 percent in 2020, and in Sweden from 33 percent to 10 percent over the same period.[2] If this trend continues or even accelerates, the role of cash and thus central bank money would decrease significantly for the benefit of private payment service providers. This would likely lead to a reduced usability of central bank money and frequency of conversion of bank deposits into central bank money. Moreover, this raises concerns about insufficient competition, inclusiveness, privacy protection as well as strategic autonomy of sovereign states.

Against this backdrop, a growing number of central banks started to prepare for the issuance of CBDC (for example the PBoC in 2014, the Riksbank in 2016, India in 2017, and the ECB in 2019). The envisaged design features of retail[3] CBDCs that consistently emerged across these CBDCs project include non-remuneration and limitation of holdings. By issuing CBDC, central banks want to *preserve* the benefits for citizens of the co-existence of central bank money next to commercial bank money (more choice for citizens and merchants, preventing abuse of market power by few dominant private firms since payments have strong network effects, preserving the anchoring of all forms of private money in an effective convertibility promise into usable central bank money) and modernizing central bank money available to citizens by allowing the advantages of electronic payments (integration into mobile phone; overcoming the need to warehouse cash in a separate wallet; reducing risk of theft; overcoming costs associated to cash including higher environmental footprint) to also benefit central bank money and not only commercial bank money.

In parallel to the actual work of central bank payment experts, a heated academic debate about CBDC began in 2016. Between 2016 and 2020, around 1100 papers have been published that contain the

[1] See ECB SPACE publication here https://www.ecb.europa.eu/stats/ecb_surveys/space/html/ecb.spacereport202212~783ffdf46e.en.html

[2] See FEDs "Money and Payments: The U.S. Dollar in the Age of Digital Transformation", here.

[3] We use the term "CBDC" for "retail CBDC" i.e. electronic central bank money available for citizens for retail payments. The BIS has also proposed the term "wholesale CBDC" but we consider this use as confusing since electronic central bank money has been accessible for banks for a long time in the form of RTGS balances. The term "retail payments" is actually used in the literature and by practitioners in various ways: some use it as referring only to payments involving natural persons, such as "POI" payments ("P2B" – person to business, essentially in physical shops and e-commerce) and P2P (person to person) payments, while others would use it for all payments which are not interbank payments, i.e. including B2B (business to business) payments. For example, the digital euro is a CBDC for retail purposes in a narrow sense, excluding B2B payments.

keywords "CBDC, central bank, models" according to Google scholar, and in 2023 alone more than 2000 such papers were added[4]. At the same time, the central banks that are considering issuing CBDC have also increasingly communicated intentions, plans and design specifications (e.g. ECB, 2023a).

Due to the growing number of papers that present macro-economic models examining CBDC and, on the other hand, quite detailed plans by central banks to issue CBDC, this paper examines to what extent the assumptions and scenarios contained in these macroeconomic models of CBDC correspond to the objectives and emerging design choices communicated by central banks and related to this, how applicable the papers' predictions of macroeconomic effects are to the CBDCs outlined or announced by central banks. The choices to be made with regards to the issuance and design of CBDC are of high importance for society, and central bankers and legislators want to understand what is at stake. It is therefore logical that both also turn to academic literature on CBDC with the assumption to find relevant predictions regarding macro-economic effects, and that both also consider basing their choices on the conclusions of this literature. The macro-economic literature aims at being policy-relevant for various key choices to be made, as also illustrated by the titles of the papers: "Should central banks issue digital currency?" (Keister and Sanches, 2023), "CBDC and the operational framework of monetary policy" (Abad et al., 2023), "Assessing the impact of central bank digital currency on private banks" (Andolfatto, 2021), "The optimal quantity of CBDC in a bank-based economy" (Burlon et al., 2022), "Central Bank Digital Currency: when price and bank stability collide" (Fernández-Villaverde, 2023), "Central bank digital currency: Welfare and policy implications" (Williamson, 2022). The papers are relying on some very specific (previously existing) macro-economic models, with few exceptions as for example Gross and Letizia (2023), and equally specific assumptions regarding how CBDC enters this model. Moreover, as will be explained in more detail in section 3, assumptions on reasons to issue CBDC and on CBDC design features often rely on an early narrative that preceded and often deviates from the related announcements of central banks.

What central banks have announced on CBDC design

In principle, a variety of CBDC designs could be compatible with the motivation of central banks to preserve the role of central bank money in payments, including the introduction of potentially unlimited, large-scale or remunerated CBDC. When CBDCs first started being discussed in 2015/2016 by central bank researchers (such as Barrdear and Kumhof, 2016/2021), uncertainty about these design features was high and central bank payment departments had not yet worked on the actual

[4] Not all of these papers may be limited strictly to retail CBDC, but the large majority is. Indeed, "wholesale CBDC" is typically considered to not have any macroeconomic consequences (see also previous footnote).

specifications of CBDCs. As payment experts progressed in their work and central banks started unveiling their actual plans, however, this uncertainty gradually dissipated. In this sense, it is natural that early academic research work on the topic features some hypothesized characteristics of CBDCs that do not coincide with the designs that were worked out by payment experts and endorsed by the central bank decision makers. When considering the issuance of CBDC, central banks have been particularly careful with regards to unintended consequences of CBDC, while they showed little appreciation for the positive economic effects that research papers considered possible through remuneration or via some quantity effects if CBDC holdings would be large. Central banks essentially approached the design of CBDC in a way to *preserve, and not to expand* the relative role of central bank money in the economy. Therefore, they also opted against using CBDC for extending their footprint on the economy at the expense of banks and thereby went against those who favored the idea to use the issuance of CBDC to move towards a "sovereign" monetary system. For example, Dyson and Hodgson (2016) considered that CBDC

> *"…can make the financial system safer: Allowing individuals, private sector companies, and non-bank financial institutions to settle directly in central bank money (rather than bank deposits) significantly reduces the concentration of liquidity and credit risk in payment systems. This in turn reduces the systemic importance of large banks and thereby reduces the negative externalities that the financial instability of banks has on society. In addition, by providing a genuinely risk-free alternative to bank deposits, a shift from bank deposits to digital cash reduces the need for government guarantees on deposits, eliminating a source of moral hazard from the financial system."*

These ideas were not endorsed in central bank narratives of CBDC, nor through the CBDC design choices they made in the meantime. Central banks, like ECB (2023a) declared that they want to *preserve* the role of banks in money creation, payments, credit provision and credit risk management, consistent with the belief that a decentralized and competitive economy is preferable and designed their CBDC accordingly. Monnet and Niepelt (2023) have criticized this conservative approach and re-emphasized the above perspective of Dyson and Hodge (2016) arguing that this approach is "sacrificing the digital euro on the altar of banking as we know it" and call for using a CBDC to rethink the fractional reserve system.

Central banks have outlined the potential negative implications of opening the central bank balance sheet to the public via an unconstrained CBDC which could serve as large-scale store of value, and thereby (i) add a further destination for deposit outflows from banks which could destabilise bank deposits (e.g. Bindseil and Senner, 2023), (ii) increase central bank balance sheets and centralise to some extent credit provision, and disintermediate banks and weaken their ability to provide a service to society (maturity transformation; credit selection and monitoring), (iii) facilitate international speculative capital flows, e.g. due to the perceived safe haven status of specific currencies. That CBDC might facilitate bank runs relative to a world in which central bank money can only be accessed (by

non-banks) in the form of banknotes has been recognized at an early stage by central banks. For example, CPMI-MC (2018, 15) already noted that:

> *"A general[5] purpose CBDC could have a large impact on financial intermediation patterns. The consequence of a larger central bank balance sheet could be a withdrawal of funding to commercial banks. For example, a flow of retail deposits into a CBDC could lead to a loss of low-cost and stable funding for banks, with the size of such a loss in normal times depending on the convenience and costs of the CBDC. …. … banks might have to shrink their balance sheets, with possible adverse consequences."*

Central banks have since acknowledged that they would need to limit potential flows into CBDC through some tools (Bindseil, 2020), and all central banks envisaging to issue CBDC, including e.g. the Bank of England and the ECB, have confirmed that they would plan to set limits on the usage of CBDC per holder, implying the need to associate all holdings of CBDC with an identified holder, so as to be able to monitor the application of such limits (see for example Panetta, 2022, for the digital euro). Central banks have mentioned different levels of possible limits (e.g. the ECB has referred to 3000 euro as example, while the Bank of England to 10-20,000 pounds, and the People's Bank of China, PBOC, to 10,000 yuan for anonymous use cases[6]). Central banks are studying in detail the calibration of limits (e.g. Adalid et al., 2022), although they emphasize that the eventual setting of a limit will rely on updated data close to the eventual issuance of CBDC.

An additional feature consistently established by central banks, that should accordingly be investigated by macro-economic models of CBDC, is the non-remuneration of CBDCs. Early discussion papers by European central banks, such as Riksbank (2017), Bank of England (2020), Bank of Canada (2020), and ECB (2020), still discussed remuneration of CBDC as one option, while Agur et al note already in 2019 (p. 3) that "all ongoing central bank CBDC initiatives center on non-interest-rate bearing CBDC". Since then, all major central banks working on CBDC have confirmed the non-remuneration of CBDC.

For example, PBoC (2021, 7) states that: "The e-CNY is a substitute for M0. Thus, it is treated the same as the physical RMB under M0, which carries and pays no interest." Similarly, the Bank of England (2023) explains in its Q&As on digital pound that: "Like a physical banknote, and many current accounts, no interest would be paid on a digital pound. This makes it useful for everyday payments but not designed or intended for savings."

[5] The report uses the term "general purpose CBDC" for what is called in the rest of the literature "retail CBDC".
[6] "accounts can hold a maximum of 10,000 yuan and daily use is limited to 5,000 yuan (625 euros). The amount available for use increases if the registrant provides their government-issued resident identity card number or links their wallet to their physical bank account. Users can gain unlimited spending on their digiyuan account if they personally identify themselves at a bank branch." See here.

The ECB (2023, 11) states "firmly" that digital euro will be developed to be non-remunerated, but also reserves its right to potentially consider remuneration in the future:

> *" It cannot be stated firmly enough that the ECB is not developing a remunerated digital euro. Indeed, as is the case for euro banknotes, the ECB does not intend to remunerate the digital euro, either at its launch or for the foreseeable future. Banknotes have never been remunerated, because it is impractical to do so, although such remuneration is neither theoretically impossible nor expressly prohibited by law. Given its mandate to maintain price stability and the concomitant basic task of defining and implementing the monetary policy of the euro area, the ECB cannot exclude future scenarios where remuneration of the digital euro might be warranted. Also, to further its monetary policy mandate, the ECB must remain in control of the remuneration of all liabilities on its balance sheet. Even if this provision were to be interpreted as an outright exclusion of remuneration, this could not, in any event, restrict the Eurosystem's primary law competence to independently define and implement the monetary policy of the euro area, as the powers set out under Article 133 TFEU are expressly stated to be without prejudice to the powers of the ECB. For this reason, an amendment is proposed to clarify the primacy of the ECB's mandate to maintain price stability and the concomitant basic task of defining and conducting the monetary policy of the euro area."*

The foreseen non-remuneration of CBDCs makes them more similar to banknotes in circulation – and makes it difficult for macro-models to meaningfully distinguish the two form of central bank money in macro-economic models. Some models try to distinguish the two forms of central bank money with their privacy features and fraud risks, and base macro-economic prediction on these differences. Others try to distinguish the two forms of central banks money by modifying the utility function of agents to have different "base utilities" for different forms of money. These issues will be taken up in subsequent sections.

Another set of key features announced for CBDCs which will determine the volume of CBDC in circulation are those that allow to somewhat decouple the store of value from the means of payments function of CBDC and that facilitate the preservation of a single pool of money for citizens, this pool being their main commercial bank money account. For example, the ECB (2023a) announced a so-called "reverse waterfall" which would function as follows (emphasis in bold added):

> *"While neither a commercial bank account nor a link between such an account and digital euro holdings would be a prerequisite for individuals to have access to digital euro services, the expectation is that many people would find it convenient to "link" their digital euro account to a designated commercial bank account for funding purposes. This would maximise payment convenience in the following ways.*
>
> - *It would always be possible to receive a payment, even if the amount to be received raises the digital euro balance above the holding limit. The excess amount would be transferred automatically to the linked commercial bank account (waterfall functionality). Users would also be able to set a threshold for this automatic transfer that is lower than the holding limit.*
> - ***Users would not need to prefund a digital euro account before making payments. If there are insufficient funds in the digital euro account, the shortfall could be transferred immediately from the linked commercial bank account (reverse waterfall functionality).***
>
> *An individual would be able to choose whether to benefit from the waterfall or reverse waterfall functions or both. Waterfalls combine funding/defunding and payment processing in a single operation, with no or very limited impact on the processing time for the user."*

Last but not least, central banks have announced access restrictions for CBDC. For example, the ECB plans to only allow natural persons who are permanent residents of the euro area (or possibly of the EU), and temporary residents (e.g. travelers) to be able to hold digital euro within the limits. Corporates and the "rest of the world" will be excluded from holding digital euro, which makes obviously an enormous difference for potential total digital euro holdings (see ECB, 2023a, section 2.1). However, the articles 18 and 19 of the digital euro draft legislation leave a back door open for allowing international holdings at some stage (European Commission, 2023):

> *"Access to and use of the digital euro in a third country is also possible, subject to two conditions as well: (1) the Union and the third country conclude an international agreement, and the third country commits to a number of conditions; (2) the European Central Bank and the non-euro area national central bank enter into an arrangement that specifies the necessary implementing measures."*

Overall, the features that central banks have announced are important for any macroeconomic consequences of CBDC. For example, the package announced by the ECB with regard to digital euro (holding limits; access limited to domestic citizens; reverse waterfall; no remuneration) restricts also the possible macro-economic consequences of CBDC to a considerable extent, as CBDC holdings will be rather low. The design features announced by central banks, such as in ECB (2023a), are obviously a consequence of earlier analysis of the financial stability risks that CBDC might create, if not prudently designed (e.g. CPMI-MC, 2018). One cannot say that they are the consequences of insights from early macro-economic modelling (such as e.g. Barrdear and Kumhof, 2016/2021), as this literature was positive about the macro-economic consequences of a remunerated, large-scale CBDC, which was more the opposite of the more recent design announcements of central banks.

Moreover, the distinguishability relative to banknotes is difficult in the context of a macro-economic model because the balance sheet effects of CBDC and banknotes are identical for the banking system.

Macro-economic literature reviewed

We review 14 papers predicting macro-economic consequences of CBDC, namely Abad et al (2023), Assenmacher et al (2023), Barrdear and Kumhof (2016/2021), Burlon et al (2022), Brunnermeier and Niepelt (2019), Chiu et al (2019), Ferrari et al (2020), Gross and Letizia (2023), Jiang and Zhu (2021), Keister and Sanchez (2023), Niepelt (2023), Piazzesi et al (2022), Fernández-Villaverde et al (2023), Williamson (2023). The selection of papers was guided by the aim of having a wide range of macroeconomic approaches by renowned economists. We believe that the papers are sufficiently diverse to get a rather comprehensive picture of the more common pitfalls in predicting macroeconomic effects of CBDC. In comparison to other reviews of macroeconomic CBDC literature (e.g. Assenmacher and Smets, 2024), we focus on a more narrow set of papers and focus on a number

of issues which may put into question the validity of some model predictions in view of the more recent narrative and design specifications of central banks (e.g. ECB, 2023a). Table 1 summarizes the papers according to their research questions, methods, and results.Our review of CBDC models differs from existing CBDC review studies such as Carapella and Flemming (2020), by contrasting them with the CBDC designs as outlined by central banks and by discussing the implications of the reactive and conservative nature of CBDC issuance in view of the profound digital transformation of money and payments which has been ongoing for years on the macro-economic modelling of CBDC. We share the finding of the review by Ahnert et al (2022) that more research is needed regarding the demand of end-users for different types of CBDC, and that the effect of CBDC very much depends on the specific design. Our findings are also in line with what Infante et al (2022) conclude in their review study, namely that CBDC raises "important questions regarding monetary policy implementation and the footprint of central banks in the financial system. Ultimately, the effects of a CBDC depend critically on its design features, particularly remuneration".

Table 1: Stylized overview of literature reviewed

Article	**Research question**	**Method**	**Results**
Abad et al (2023)	Effect of CBDC on operational framework and macroeconomy	New Keynesian model with money in utility function, applied to Euro Area	Moderate CBDC adoption leads to transition from floor to corridor system, higher adoption leads to banks taking recourse to central bank credit; small effect on real economy
Assenmacher et al (2023)	Effect of CBDC on business cycles	New Monetarist and New Keynesian	Remunerated CBDC helps smooth responses to macroeconomic shocks
Barrdear and Kumhof (2021)	Effect of CBDC on macroeconomy	New Keynesian calibrated to US	Remunerated CBDC can increase output and stabilize business cycle
Burlon et al (2022)	Optimal level of CBDC	New Keynesian	15-45% of GDP as optimal amount of CBDC in EA; trade-off between positive effects of CBDC (smoothening business cycle) and risk of bank disintermediation
Brunnermeier and Niepelt (2019)	Effect of CBDC on macroeconomy and financial stability	New Keynesian and New Monetarist with cash in advance constraint	No effect on macroeconomy and financial stability if pass-through policy of central bank
Chiu et al (2019)	CBDC effects on bank deposit and lending in case	New Monetarist	When banks have market power in the deposit market, issuing a deposit like CBDC

	banks have market power		with a proper interest rate increases deposits with banks and bank loans
Ferrari et al (2020)	Macro-effects of CBDC in a two-country model focusing on international spill-overs	Two-country New Keynesian model with money in the utility	CBDC amplifies international spillover of shocks and international linkages
Gross and Letizia (2023)	What is CBDC-in-total-money share and effect on banks' profits and monetary policy pass-through	Stock-flow consistent model with game theory, reinforcement learning and money in the utility function	Upper bound estimates for the CBDC-in-money shares: 25% in US, and 20% in EA, when CBDC would be remunerated at the policy rates and be perceived as "deposit-like" by the public.
Jiang and Zhu (2021)	Effect of CBDC on monetary policy pass-through	New Monetarist	CBDC can strengthen or weaken the pass-through depending on competitiveness of deposit market and interest rate on reserves relative to rate on CBDC
Keister and Sanchez (2023)	Should central banks issue CBDC	New Monetarist	CBDC improves efficiency in exchange, but it may crowd out bank deposits, raise banks' funding costs, and decrease investment.
Niepelt (2023)	Role and optimal amount of CBDC	Neoclassical with money in the utility function	Interest rates on CBDC and reserves should differ; optimal share of CBDC in payments tends to exceed that of deposits
Piazzesi et al (2022)	Role and effect of CBDC on real economy	New Keynesian	Remunerated CBDC has real effects; effects on inflation and output in a contractionary policy are half the size compared to a non-CBDC world
Fernández-Villaverde et al (2023)	Effect of CBDC on monetary policy	Diamond and Dybvig-type	With CBDC, a central bank can achieve only two of the three goals: financial stability, price stability, or efficient allocation of resources
Williamson (2023)	Effect of CBDC on welfare	New Monetarist	CBDC can increase welfare by competing with private money and by disintermediating banks

Structure of the paper

The paper is structured as follows. Sections 2-6 review each one of the key issues that may undermine the reliability of the predictions of the macroeconomic models of CBDC. Section 2 covers the issue of not taking into account the nature of central banks' CBDC issuance plans as a "conservative" reaction to technological and preferential shifts in the use of money as a means of payments (issue i). Section 3 is about not considering yet the design features communicated by central banks so far (partially only in 2023), such as no-remuneration, quantity limits and access restrictions, and automated sweeping functionality linking CBDC wallets with commercial bank accounts ("reverse waterfall"). This sometimes includes assuming that CBDC would be used as monetary policy instrument, or for other purposes that central banks reject (issue ii). Section 4 discusses the insufficient explanations of the differences between CBDC and banknotes within macro-economic models (issue iii). Section 5 discusses an issue that results from the previous three points, namely assuming with no or insufficient justification that CBDC will lead to a significant increase in the total holdings of central bank money in the economy (issue iv). Section 6 looks at the papers' predicted macro-economic consequences of CBDC. Section 7 of the paper turns to the more general issue of macro-modelling and the search for realistic assumptions and policy relevance. Section 8 concludes.

2. CBDC issuance plans as a "conservative" reaction to technological and habit changes

None of the macroeconomic models of CBDC incorporate the strong changes that digitalization is currently bringing for payments and the use of money, even if some of the papers acknowledge in their introductions the reasons of central banks to prepare for possible issuance of CBDC. When studying and preparing the possible issuance of central bank money, central banks *react* to technological and preferential shifts in the use of money as a means of payments, notably the ever-increasing reliance of citizens on electronic means of payments, and the implied lesser reliance on central bank issued cash. Central banks according to their announcements do not aim to change the monetary system by issuing CBDC, but at *preserving* the role of central bank money in a more and more digitalized society. The continued use of central bank money by society is considered important because (i) it provides a risk free mean of settlement; (ii) it anchors the two-layer monetary system as commercial bank money is a convertibility promise into central bank money (which also requires to be testable in reality); (iii) central bank money can incorporate public-good related features which may be less attractive for profit-seeking private money issuers (such as inclusiveness and privacy

protection); (iv) the competition of private and public means of payments constrains the potential abuse of market power by dominant private actors in the payment industry, which exhibits strong network externalities; (v) it contributes to geopolitical resilience and strategic autonomy of countries, in particular if the dominant privately issued payment instruments are from global companies headquartered abroad. See also Gross and Letizia (2023) as well as Boar and Wehrli (2021) for a discussion of central banks' motives for considering CBDC.

Preserving the role of central bank money in times of technological change and shifting consumer behavior implies a need to renew the form of central bank money and make it fit for the scenario of a further and further digitalization of retail payments. This consideration is strongly supported by data: in the euro area, for example, the share of cash payments at the point-of-sale (i.e. in physical shops) declined from 79% to 59% between 2016 and 2022, mainly for the benefit of card payments.[7] Overlay-solutions like ApplePay enabling seamless mobile payments at the point of sale based on an underlying card seem to recently even accelerate this trend at the point of sale. On top, e-commerce, which relies by nature on electronic payments, is gaining an ever-larger market share, implying an even steeper digitalization trend in payments than what the number at the point-of-sale suggest. Most euro area citizens (55%) now prefer electronic payments, and this number will increase further year-by-year. These trends are also pronounced in other countries. In the US, cash use fell from 40 percent in 2012 to 19 percent in 2020, and in Sweden from 33 percent to 10 percent over the same period.[8]

The macroeconomic models of CBDC instead treat the decision to issue CBDC as out of nowhere, i.e. as if there would not be an ongoing pervasive change in the forms of money used for retail payments to which issuing CBDC is a reaction. They instead consider the technology and the demand of society for different means of payment as static and assume that the central bank enters this static market with a new product, which then modifies the equilibrium of the market and has macroeconomic consequences. Modeling the endogenous central bank response may be relatively difficult, and could be qualitatively motivated to some extent, but the demand for banknotes as well as CBDC should at least not be ad-hoc exogenous, but part of the model.

The approach taken in macro-economic models to introduce CBDC ad-hoc can be traced back to CMPI-MC (2018, 25) and Bindseil (2020, 10). Flow of funds were presented there as in figure 1, starting from the assumption that banknotes are given and that when CBDC is introduced, the key question is to what extent it either substitutes banknotes (**CBDC1)** or deposits of banks (**CBDC2**). The former is neutral

[7] See ECB SPACE publication here https://www.ecb.europa.eu/stats/ecb_surveys/space/html/ecb.spacereport202212~783ffdf46e.en.html
[8] See FEDs "Money and Payments: The U.S. Dollar in the Age of Digital Transformation", here.

from a macro-economic point of view (starting from the fact that financial accounts remain unchanged), while the second requires banks to substitute one relatively cheap and stable funding source, household deposits, with alternatives which are at least likely to be more expensive. At the same time, CBDC2 allows the central bank balance sheet to grow, potentially increasing seigniorage income and thus profits disbursed to governments, etc. This approach is also visible in a speech by Bank of England's Broadbent (2016, 2), where, without showing flow of funds explicitly, it is discussed to what extend the introduction of CBDC would substitute deposits or cash away, implying that CBDC would affect an otherwise static situation.

If we however consider the Scandinavian countries or other countries in which digitalization of payments has gone very far, we observe that before any issuance of CBDC, the circulation of banknotes significantly decreased for the benefit of household deposits with banks, and it is this effect that triggers analysis of central banks to possibly issue CBDC, to address the effects of digitalization on payments and preserve a role for central bank money. For example, in Sweden the nominal amount of cash in circulation declined in nominal terms by 50% since 2006 (according to the 2022 payments report of the Sveriges Riksbank). We add this initial effect which is the trigger of all other effects as "**DIG**" for DIGitalization effect. **DIG** may well exceed **CBDC2** and it may even exceed **CBDC1+CBDC2** – this would certainly be the case if a CBDC is designed in a way to strongly discourage the store of value function.

Figure 1: Financial accounts impact of CBDC as in CPMI-MC (2018) and Bindseil (2020)

Households	
Other Assets Sight deposits **+ DIG** **- CBDC2** Savings + time deposits **CBDC** **+CBDC1+CBDC2** Banknotes **- DIG -CBDC1**	Household Equity Bank loans
Commercial Banks	
Other assets Central bank deposits	Sight deposit **+ DIG** **- CBDC2** Central bank credit **- DIG** **+ CBDC2**
Central Bank	
Credit to banks **- DIG** **+ CBDC2** Other assets	Banknotes issued **- DIG -CBDC1** Deposits of banks **CBDC** **+CBDC1 +CBDC2**

It may also be asked why in macro-economic models, a change of technology of central bank money should appear to have important effects, while the change of technology of commercial bank money which is leading the digitalization of money (and has led to shifts in the relative role of commercial-bank and central bank money in payments at the expense of the latter) is ignored or not considered

relevant. The importance of this point is also illustrated by the counter-factual: if central banks were to not issue CBDC in an economy which moves fully towards digitalization, the role of central bank money for citizens would vanish. Instead, few private providers of payments instruments would dominate the market and have more and more leverage to abuse market power and make payments more expensive, with negative macroeconomic consequences. The convertibility test (private money being defined as a promise to be converted "at sight" into central bank money) would become inapplicable, which would reduce market discipline and presumably undermine financial stability, etc.. Issuing CBDC makes more likely that the relative role of central bank money in payments and money stocks is stabilized and therefore it is plausible that introducing CBDC is less disruptive also from a macro-economic perspective than not introducing it.

None of the fourteen reviewed macro-economic papers builds this endogeneity into their model and discusses the macroeconomic effects of the shifts in payments technology and habits in the scenario of central banks sticking to paper money issuance only and being gradually crowded out. Instead, all consider CBDC issuance to be an exogeneous model event in a static monetary and payment system. This problem is independent of the gap between CBDC design features announced by central banks and the ones assumed by macroeconomic researchers.

Some of the papers (Assenmacher, 2023, Ferrari et al, 2020, Keister and Sanchez, 2022, Williamson, 2023, Gross and Letizia, 2023) acknowledge in their introduction that CBDC issuance would be a reaction to changes in payments technology and habits. But even these papers do not consider this further in their modelling approaches and thus in the prediction of macroeconomic effects of CBDC issuance.

A number of papers (e.g. Burlon et al, 2022) present the decision to issue CBDC and to specify a supply rule as exogeneous while the demand for banknote declines only as a consequence of the issuance of CBDC, but not because of ongoing digitalization. Niepelt (2023) studies " 'disruptive' deposit-CBDC substitution of relevance for the banking sector and the macro economy" (p. 38). Gross and Letizia (2023) model a different demand for CBDC and banknotes, which in principle could also be specified in such a way that a technologically induced decline in the demand for banknotes induces a higher demand for CBDC.

Other papers portray CBDC as a reaction to something that is not very relevant for the use of central bank money or the change in payments. Barrdear and Kumhof (2016/2021) motivate CBDC with the emergence of private digital currencies like Bitcoin, although Bitcoin has not played a role in the shift towards digital retail payments during the last decade. Moreover, the authors explicitly exclude any room for how central banks react to digitization by abstracting "away from the technological

particulars of how a CBDC payment system might operate" (p.2). Similarly, Brunnermeier and Niepelt (2019) refer to how Fintechs and Bigtechs "supply new digital monies" (p.27) without explicitly describing the role of these moneys in payments (although the general liquidity function can be interpreted as capturing all sorts of micro-structure issues of payment instruments).[9]

3. Consistency with CBDC design outlined by central banks and legislators

Macro-economic models of CBDC tend to assume that CBDC volumes will be significant and/or that CBDCs will be remunerated, so that again CBDC volumes will be significant as a consequence. The macro-economic effects predicted depend on these assumptions. However, as summarized in the introduction, CBDCs like the digital euro will not be remunerated and will likely only have relatively low volumes (due to non-remuneration and other specific features) and may not even necessarily be compensating the future declining demand for banknotes.[10]

Ignoring holding limits or equating limits with supply

Most papers ignore the fact that all central banks working on CBDC have announced limits, or, if they mention it, do not model it explicitly or do not show the respective simulation (Gross and Letizia, 2023, 25). One paper acknowledges limits in one model variant (Burlon et al, 2023, 22), but equates limits with a non-elastic supply function of CBDC, i.e. a "verticalist" view of monetary policy implementation. Setting limits is however not at all equal to setting the supply of CBDC. CBDC holdings will, within the limits, be demand driven. For example, the digital euro's combination of limits, reverse waterfall, and no remuneration implies that actual digital euro holdings can be expected to be on average far below what the limits would allow.

Also, Assenmacher et al. (2023, 22) consider variations in CBDC supply to stabilize the economy:

> *"A high deposit rate indicates stressed bank funding conditions and low deposit holdings. In such a situation, a decrease in CBDC supply increases the transaction value of money and leads to a higher liquidity premium […]. This […] eases banks' funding costs. In addition, a decrease in CBDC supply crowds in deposits as households substitute CBDC for deposits. The CBDC rule thus stabilises the economy through a stabilisation of bank funding conditions in the face of financial stability shocks."*

[9] Note that Bitcoin and similar projects are not to be classified as money or currencies (see for example Chanson and Senner, 2022).
[10] Baeriswyl et al (2024), for example, argue that CBDC with quantity limits is "likely to discourage the use of CBDC as a medium of exchange".

It may be noted that regardless of its application to CBDC, the idea that central banks control the supply of components of, or of the entire monetary base as policy instrument has been rejected for a while by a variety of authors (e.g. Goodhart, 1984, Moore, 1988, or Bindseil, 2004) and central bank practitioners.

More recent macroeconomic papers such as Assenmacher et al (2024) and Bidder et al (2024) explicitly discuss the role of limits to contain unintended macro-economic consequences.

Ignoring sweeping facilities like the digital euro's reverse waterfall

We are not aware of any macroeconomic model that already tries to incorporate the automated sweeping functionality linking CBDC wallets with commercial bank accounts (waterfall and "reverse waterfall"), and which acknowledges its strong effects (in combination with limits and no remuneration) on the demand for CBDC holdings. Such facilities are announced in ECB (2023a). With such facilities, it is attractive for users to use digital euro without prefunding digital euro wallets, somewhat similar to the way PayPal is typically used. In cases of systemic financial instability, CBDC holdings could be less affected by such sweep facilities, which could be incorporated in macro-economic models of financial instability.

Remuneration and/or active use as monetary policy instrument

Despite the announcement of central banks to not remunerate CBDC, many macroeconomic models of CBDC focus on the earlier narrative with remuneration (Assenmacher et al, 2023; Barrdear and Kumhof, 2021; Brunnermeier and Niepelt, 2019; Andolfatto, 2021; Piazzesi et al, 2022), or have remuneration play at least a prominent role in some of their model scenarios. For example, in Brunnermeier and Niepelt (2019), CBDC is not limited, is remunerated and the remuneration is potentially equal to the one of deposits held with banks. Similarly, Niepelt (2023) presents a model with a variable interest rate on CBDC as well as a potentially unlimited size of CBDC. The model of Andolfatto (2021) also relies on CBDC being remunerated whereas cash is not. Keister and Sanches (2023) analyze three different types of CBDC forms, where all types of CBDC have in common that they can have an interest rate remuneration. CBDC in the model of Barrdear and Kumhof (2016/2021) resembles a remunerated central bank bill that is issued to retail investors in exchange for government bonds. Finally, Piazzesi et al (2022) present a model where the CBDC version of the model also features remunerated accounts.

Notable exceptions are Burlon et al. (2022) who do not only model interest bearing CBDC but also a CBDC design without remuneration but where the central bank controls supply. In Burlon et al (2022) large-scale CBDC has the potential to affect the business activity of banks, "which tends to adversely affect bank lending supply and real GDP." Moreover, Abad et al (2023) also study non-remunerated CBDC ("The core of our analysis is on the long-run effects of introducing non-remunerated CBDC."), but the effects of CBDC in the model are equivalent to the effects of an increase of banknotes in circulation (i.e. relate to the increase of total central bank money in circulation). Gross and Letizia (2023, 6) also focus on remunerated CBDC, but not exclusively, also discussing the effects if remuneration would be zero ("With zero or low CBDC interest rates, seigniorage first rises due to higher interest income from reserve lending."). Some assume constant remuneration and explicitly reject the idea that changes to interest rates on CBDC are used as an active monetary policy tool (e.g. Williamson, 2021). Ferrari et al (2020) foresee the possibility of remuneration and some but not all model-effects of CBDC relate to it. Chiu et al (2019) assume remuneration to achieve the best possible positive effect of CBDC on the efficiency of an oligopolistic banking system.

Several macroeconomic models introduce CBDC as a novel instrument to improve monetary policy and other specific purposes that central banks have not taken up. The instrument parameter can consist either in the remuneration of CBDC (see Assenmacher et al, 2023, Niepelt, 2023, and Keister and Sanches, 2023), or in an assumed "vertical" CBDC supply curve, whereby the supply quantity would become the policy variable (Piazzesi et al, 2022), or both (Barrdear and Kumhof, 2016/2021; Burlon et al, 2023). These assumptions do not match the more recent announcement of central banks, and either relate to earlier CBDC narratives, or to "verticalist" views on monetary policy implementation not applied by central banks in practice since the 1990s.

Gross and Letizia (2023) find that the introduction of CBDC can lead to a lower bank profitability, higher central bank seigniorage, and a decrease in the bank deposit-policy rate spreads, *strengthening monetary policy pass-through*. Assenmacher et al (2023, 4) also conclude that "the existence of a CBDC provides the central bank with a *second policy instrument* that allows the central bank to stabilise the liquidity premium, defined as the spread between the interest rate on CBDC and bank deposits relative to the return on government bonds." Niepelt (2023) sees CBDC as an additional policy instrument next to central bank reserves, whereby "policy" in this case however simply consists of charging a liquidity premium that covers the social costs. The optimality of the central bank's monetary policy refers to how it manages both reserves and CBDC, and it is found that "CBDC and reserves should be remunerated differently" (Niepelt 2023, 36). In Keister and Sanches (2023) the interest rate on CBDC is also seen as a new policy instrument and "can be used to influence the efficiency of exchange and, in some cases, of aggregate investment" (p. 405).

Jiang and Zhu (2021, 3) argue that CBDC enhances the effectiveness of monetary policy because *"the CBDC rate has stronger pass-through to the deposit market than the reserve rate when the deposit market is not perfectly competitive. This is because banks do not fully pass the increase in the reserve rate to depositors as a higher deposit rate when they have market powers on the deposit market and households cannot directly hold reserves. In contrast, the CBDC is a perfect substitute for deposits as an electronic means of payment, so the bank is forced to match the CBDC rate one for one."* Moreover, they see scope for a distinct, non-redundant use of the "reserve rate" (i.e. the normal operational target of monetary policy) and the remuneration rate of CBDC: *"In a world with an imperfectly competitive deposit market, the central bank can boost lending and hence output by increasing the CBDC rate while keeping the reserve rate constant or even reducing it."* From a practical central bank perspective, one may wonder if this might not overengineer monetary policy, i.e. making it too complex and pushing it beyond a realistic view of our understanding of the transmission mechanism. Such ideas might somehow remind the enthusiasm for some decades in the 20th century for using active changes of the reserve requirements ratio as a further *non-redundant* monetary policy instrument that would enrich the set of feasible macro-economic outcomes relative to only using the short-term interest rate. Following ideas of Keynes from the 1930s, indeed, both the Fed and the Deutsche Bundesbank (and many others) frequently changed reserve requirement ratios from the 1950s to the 1970s, explaining this as an additional independent monetary policy instrument (see Bindseil, 2004, 23-24). It was subsequently given up for the sake of a simpler, more transparent, and equally effective monetary policy implementation approach (controlling short term rates).

Economists and the remuneration of CBDC: vision and reality

The non-remuneration of CBDCs as announced by central banks is frustrating for some economists at least from two perspectives. The first perspective is the one of the macro-models reviewed, which consider the remuneration as a useful independent additional monetary policy tool which would allow improving macro-economic outcomes at least in some cases.

However, there is also a second perspective, taken for example in Bindseil (2020), which is somewhat the opposite: remunerating CBDC would not be a matter of an additional monetary policy instrument, but of correcting the anomaly that banknotes are unremunerated. On one side, it is sensible that a financial asset with exceptional liquidity properties and providing utility beyond the investment return has in equilibrium a lower rate of remuneration than less liquid assets which serve as investment. However, this does not imply that their remuneration is always zero, and that it is so regardless of whether the nominal interest rate on other short-term central bank liabilities such as reserves is at

around -0.60% (euro area in 2020) or 4% (euro area in January 2024) or 45% (Turkey in January 2024). This anomaly creates macroeconomic non-neutrality if the stock of banknotes is material. If the interest rate elasticity of banknotes demand is low, then changes of nominal interest rates will have sizable redistributive income effects (higher interest rates shift income from households to the central bank/government). If the interest rate elasticity of the demand for banknotes is high, then changes of interest rates will create significant flow of funds between banknotes and deposits with banks (with corresponding implications on the size of the central bank balance sheet and on the dependence of banks on central bank funding). From a more micro-economic perspective, the non-remuneration leads to deviations from the optimal holdings of banknotes in view of their services to the holder. For example, if nominal interest rates are high, users of unremunerated banknotes will reduce their holdings of banknotes (to reduce lost interest rate income) and go more often to the ATM to refill their (low) stocks of banknotes, with the additional time and effort spent on this activity being an indicator of the welfare loss of society.

While for banknotes, such unintended macro- and micro-economic side effects of no-remuneration have been accepted as inevitable, economists were tempted to assume that CBDC, not being subject to the same technical constraints, would be remunerated to allow overcoming them. Bindseil (2020) extended this basic assumption by proposing a two-tier remuneration which would foresee remuneration in a rule-based manner relative to ECB policy rates (i.e. not as independent policy rate). This would have achieved more stability of remuneration relative to the general interest rate level and at the same time would have ensured that CBDC would not become an investment vehicle (by also factoring in the liquidity and payments utility of CBDC).

Instead, decision makers in central banks and legislative bodies typically both rejected remuneration and concluded that the amount of CBDC holding per capita should be limited. For many economists (of both perspectives), this non-remuneration appears as a lost opportunity, and the idea of a limit on a means of payment in a world in which all other means of payments instruments are unlimited (banknotes, bank deposits, e-money, stablecoins, etc.) must have appeared almost shocking for many economists. With the reverse waterfall sweep facility, the ECB however designed a good mechanism that would allow the digital euro to work as an effective means of payment despite a holding limit.

Remunerating CBDC was presumably rejected, for example in the case of digital euro, due to a number of factors: First, non-economists may generally be sceptic with regard to the price mechanism and may lack trust into its effectiveness and fairness. Second, many banks preferred to see CBDCs be as constrained as possible, to protect deposits and maybe generally to make a scenario more likely where commercial bank money would gradually crowd out central bank money from retail payment with

ever increasing digitalization. Excessively constraining the usability of CBDC would support a scenario in which CBDC would flop. Moreover, potential *positive* remuneration would have intensified the possible competition of CBDC with bank deposits. Not remunerating CBDC both prevented this potential extra competition, and in some sense implied the need for limits. Finally, some from the liberal and conservative spectrum feared the option of *negative* remuneration, and that the central bank may have in mind to discontinue banknotes and then overcome the zero lower bound and impose significant negative interest rates, as considered in Rogoff (2016).

In any case, economists will need to accept the reality that CBDCs will not be remunerated for the foreseeable future, and that circulation will be subject to individual holding limits. Therefore, economists should devote their energy to this reality, and not to a hypothetical alternative world, one which, understandably, economists will often find more appealing. Economists who want to continue researching on *remunerated* central bank digital currency may want to differentiate their terminology, and call their subject "central bank remunerated deposits", CBRD, instead of CBDC. "Deposits" has stronger connotation of remuneration, while one is used to the fact that "currency" is unremunerated.

4. Differentiation between CBDC and banknotes

In view of the motivations provided by central banks for considering issuing CBDC (reacting to the lesser usage of cash), and the implied design choices towards introducing a type of CBDC that comes close to cash, it appears challenging for macro-models to differentiate between the two and to derive prediction from a macro-perspective based on this differentiation. And indeed, the macroeconomic literature struggles with this issue, and often introduces CBDC as a clearly distinct form of money for reasons that cannot be derived from the design outlines of central banks. However, future research could potentially adjust the elasticity of substitution between different forms of money in some models to make it closer to the design that central banks have planned.

(a) Remuneration as a distinguishing factor

As explained in the previous section, many models distinguish CBDC from banknotes through remuneration. Model results relying on this distinction can by definition not be used to assess macro-economic consequences of non-remunerated CBDC, i.e. of the CBDC that is being considered by central banks.

(b) Privacy as a distinguishing factor

Some models distinguish between CBDC and banknotes in terms of privacy. For example, Williamson (2022) explains that

> *"In our model, it is assumed that privacy in transactions can only be provided by the central bank, via currency or CBDC. We then focus on the different implications of having central bank liabilities that are an integral part of private deposit contracts vs. a world where there is public access to CBDC accounts with the central bank." (p. 2) "[A]ssume that physical currency is inferior to CBDC and bank deposits, in that physical currency cannot be used in transactions where buyers choose to forego privacy. For example, physical currency cannot be used in online transactions." (p. 7) "Assuming that CBDC allows privacy, and can also be used in all the transactions for which buyers might otherwise use bank deposits, depositors might potentially choose to defect entirely from private banking, and use CBDC in all transactions." (p 11)*

Williamson (2022) relies on the model of privacy in payments of Kahn et al (2005). This paper explains the distinction between what the author call "credit" (but which appears essentially to be non-anonymous electronic payments) and "money" (which is equated to cash like anonymity). The authors explain:

> *"The value of money also derives from its use in anonymous exchanges, facilitating certain otherwise-infeasible transactions. This property of money is most often associated with various types of shady deals, but we will argue that it is of potential social value in economic situations where the parties in the transaction cannot trust each other not to take subsequent opportunistic actions…" (p. 2) "The increasing incidence of identity theft and related frauds suggests that this is more than a theoretical possibility. A recent survey by the Federal Trade Commission … found that over 12 percent of Americans have been victims of identity theft within the past five years." (footnote page 2). "we allow them [payers] the following two choices: they may anonymously purchase goods with money, or they may choose to reveal their identity to their suppliers (and no one else) with the intent of obtaining credit for future reciprocal actions. … a credit purchase exposes the purchaser to the possibility of theft from the supplier. Depending on the model parameters, money, credit, or both may be used in equilibrium. Credit alone will be used, for example, if there is no theft and if agents are patient enough. Money will be used exclusively if the likelihood and cost of theft is high enough. We can also show that there are equilibria where both money and credit exist."*

This view of privacy however seems to be a very narrow one, and how privacy feeds into the model seems limitedly related to predominant effects in reality. Electronic payments without anonymity do not have to resort to credit, but are increasingly based on instant payments, in particular in countries with the most modern electronic payment solutions (e.g. India, Brazil, Sweden). Second, anonymity does not protect from fraud. Quite the contrary, in many situations, anonymity can facilitate fraud as it may prevent a sufficient data trail to allow law enforcement to pursue the fraudsters. Moreover, cash is subject to theft, which is the reason why people feel often more secure with electronic payment means secured by strong authentication.

Agur (2019, 1) assumes that cash provides anonymity while deposits are more secure and that "a CBDC can take any point on this interval, depending on its design". Indeed, the anonymity features of CBDC

can be specified to some extent by design (and assuming necessary legal adaptations), while one would assume that central banks always opt for a design maximizing security. One may also note that the legislator could, instead of deliberately preventing anonymity in commercial bank-based payment instruments impose higher privacy or even some forms of anonymity (i.e. this would not seem to depend on whether a payment instrument is based on central bank or commercial bank money).

Therefore, although privacy is indeed an important objective of CBDC design, and some central banks have announced even a differentiation of CBDC use cases across privacy features (like Williamson does), the way privacy is eventually modelled in the academic literature narrows down the matter to effects that are unlikely to dominate in practice.[11]

(c) Storage costs as a distinguishing factor

Burlon et al (2022, 4) differentiate cash from CBDC by assuming that cash has storage costs whereas CBDC has not. The model of Ferrari et al (2020) also features storage costs for cash. Indeed, storage costs for cash can be high and tend to increase in a non-linear way with the volume of cash. However, considering the relatively small holding limits of CBDC that central banks envision for each citizen, it seems unlikely that significant effects could be deducted from it. The assumptions about the volumes of CBDC in the model of Burlon et al (2022) could be adjusted, and the resulting macroeconomic effects reviewed accordingly.

(d) Assuming advantages to diversify across forms of money

Assenmacher et al (2024) present a model where the introduction of CBDC provides an additional financial instrument which is valued by agents from an investment diversity perspective:

> *"CBDC provides variety to the menu of monetary instruments available, which households value: their marginal utility decreases in the amount of each type of instrument held."*

Similarly, Abad et al (2023) present a New Keynesian model with CBDC, cash and deposits, and assume that "deposits, cash, and CBDC are assumed to be imperfect substitutes, and enter in the household's preferences". The introduction of CBDC then affects the demand for notes and deposits because: "The

[11] Ahnert et al (2022) also offer a model which differentiates cash and CBDC along the anonymity dimension. Initially there is only physical cash, which is anonymous, and deposits, which are convenient for online payments. CBDC then introduces an anonymous and digital payment system: "We think of CBDC as a digital version of cash. In our context, this means that CBDC enables sellers to conduct online sales (like deposits), but at the same time does not reveal any information to the bank (like cash)…. In this setting, an anonymous CBDC improves welfare because it enables merchants to get the best of both worlds. They can remain anonymous, but still reap the benefits of distributing their goods online."

reason is that cash, deposits, and CBDC are partial substitutes, and the increase in the demand of one of them implies a relative reduction in the demand of the others."

However, assuming that more diverse financial assets enhance the utility of agents would hold true for any new form of money and is not CBDC specific. In reality, when it comes to money, people value to have a single pool of liquidity, and not to fragment this pool excessively (and this is why payment instruments that do not fragment the pool of liquidity, like card schemes or e-money wallets like PayPal are so successful). Forms of (non-remunerated) money do constitute a pool of investments where a portfolio generates positive income-risk effects. Central banks have emphasized that they do not want CBDC to be a form of investment and a large-scale store of value. Instead, the ECB has discussed possibilities to link CBDC accounts to commercial bank accounts to take account of the fact that agents value a single pool of liquidity.

(e) Assuming the absence of banknotes

Assenmacher et al (2023) assume that there is no physical cash and that "CBDC and deposits are perfect substitutes and essential to pay for consumption". Similarly, there is only one type of central bank money in Brunnermeier and Niepelt (2019) which the authors describe as. Piazzesi et al (2022) present a New Keynesian model where money is part of the utility function of agents. One version of the model features remunerated accounts at the central bank for everyone while banks, commercial bank deposits as well as banknotes are absent. The authors interpret this model version as a macroeconomic model with CBDC ("Our interpretation is that there is a central bank digital currency (CBDC)", p.7). Moreover, going back to the verticalist view of central banks, the authors also assume that the quantity of money, which is here equal to CBDC, is set by the central bank: "the central bank sets the quantity as well as the interest rate on money, as opposed to the short rate of the representative agent's stochastic discount factor."

In the same spirit, Niepelt (2023, 8) assumes that there are no banknotes as they would be irrelevant: "We abstract from cash and government bond holdings. Except for effective-lower bound considerations, which are secondary in our model without price rigidities, including cash as a third retail means of payment would be largely irrelevant".

Barrdear and Kumhof (2016/2021) also assume that there are no banknotes: "We also abstract away from … physical cash, the latter due to its small size, its endogenous supply, and its different use case from electronic means of payment." Instead, the authors see CBDC as an "interest-bearing central

bank liability that competes with bank deposits as medium of exchange" and as an "an imperfect substitute for bank deposits" (p.2).

(f) Assuming unspecified differentiation through the utility function

Like many other models, agents in Gross and Letizia (2023) gain utility from the interest rates paid on CBDC or deposits. However, in addition, agents have a distinct "base utility" for all three forms of money, CBDC, cash and deposits. The base utility level can be set to equal or different levels across forms of money. For example, the authors model cash-like CBDC by setting the base utility of cash equal to the base utility of CBDC. Gross and Letizia (2023, 24) suggest that the levels of such base utilities cannot be easily linked to real world features and therefore not easily quantified, but they discuss the defining elements such as default risk, deposit insurance or anonymity, so that the model structure provides a general framework that would have to be tailored to specific CBDC designs such as the ones communicated by central banks more recently.

(g) The overall comparison of cash, deposits and CBDC by Ferrari et al (2020)

Ferrari et al (2020) provide a particularly diligent comparison of the properties of different forms of money in their Table 1 (p. 9). We reproduce their table below while omitting their line for Bonds as these seem less relevant in our context. The "X" represent the features assumed by Ferrari et al, while the "[]" and "O" have been added by us: the "[]" refer to features that could be questioned (see explanations beneath table) and the "O" are features one may consider as relevant.

Figure 2 (adapted from Ferrari et al, 2020): features of different forms of money.

	Scalability	Liquidity	Safety	Interest rate	International use
Cash	**O**	**X**	**[X]**		**X**
Deposits	**[X]**	**O**	**O**	**X**	**O**
CBDC	**[X]**	**X**	**[X]**	**[X]**	**[X]**

While the reasons for the description of the features by Ferrari et al (2020) is understandable, a close look at the assumed features also illustrates how difficult the task is to distinguish between different forms of money in practice. For example:

- **Scalability**: In theory Cash could appear less scalable than CBDC and deposits because of storage costs, but in practice CBDC will be limited (e.g. digital euro to an order of magnitude

of a maximum 3000 euro per resident) while cash is still used in some countries as massive store of value by relatively few, often for tax evasion or related to other illicit payments. Moreover, deposits have scalability problems at least for corporates and NBFIs in view of credit risk considerations (while CBDC and cash are credit risk free and exposures to central banks are typically not subject to credit risk limits).

- **Liquidity** of deposits seems as high as the one of cash and CBDC unless we consider term and saving deposits. The definition of sight deposits is to be convertible at any time into central bank money. With 24/7 instant payments, this transferability of deposits has increased further.
- **Safety**: CBDC indeed seems safer than deposits as the central bank cannot default on its obligation due to illiquidity. However, ranking deposits and cash in terms of safety is not clear as deposits benefit from deposit insurance (up to 100,000 euro in the EU) and cash can be stolen more easily. Both CBDC and deposit are subject to cyber-crime and fraud and could therefore also be under some circumstances riskier (instant payments have been significantly increasing the scale of fraudsters' attacks on bank accounts).
- **Interest rate**: all central banks working on CBDC have announced to not remunerate (as already noted by Agur et al in 2019).
- **International use**: Cash in particular in the form of USD and to a lesser extent euro circulate globally (and in any case without any limitations), while for example digital euro has been announced not to be allowed to circulate freely abroad. At the same time, correspondent banking is about offering deposit accounts to foreign banks or corporates for the purpose of making those available for international usage.

In view of these difficulties to really come up with solid differentiations of features of money that can be built into macro-economic models, it appears that the related efforts of most macro-models are insufficient, since they pretend to specifically capture the effects of CBDC relative to a world in which banknotes would be the only form of central bank money in circulation.

5. CBDC leading to significant increase in central bank money holdings

As argued in section 2, plans of central banks to issue CBDC are not an exogeneous event of which the impact can be assessed as such. The decision to issue CBDC is a reaction of central banks to digitalization, a reaction that aims at stabilizing the well-tested monetary system in which central bank

and commercial bank money co-exist, and the latter is a convertibility promise into the former that can and is tested with a very high frequency. From this perspective, macro-economic modelling attempts of the impact of the change in payment technology should focus more on the scenario in which central banks would not issue CBDC, digitalization would continue, and the role of central bank money outside the banking system would gradually disappear. At least, there is no reason why macroeconomists seem to start their work from the opposite, far less plausible assumption that introducing CBDC happens in a static monetary world and is not a reaction of the central bank to technological and preferential shifts.

Relating to this problem, a number of macroeconomic models assume that CBDC will lead to a significant increase in the circulation of central bank money in the economy and build the macro-economic consequences on that assumption. While some models simply assume a sizeable additional share of CBDC in total money holdings, others assume that this is due to a sufficiently attractive remuneration of CBDC that attracts significant volumes of commercial bank deposits to be converted into CBDC.

Abad et al (2023) modify the utility function of households so that the desired level of CBDC holdings varies, increasing the overall share of central bank money: "For instance, a level of CBDC adoption equivalent to 20% of GDP reduces bank deposits by 15% of GDP" which would suggest that only 5% of CBCD originates from a substitution of banknotes.

Assenmacher et al (2023) assume that the amount of CBDC as a share of total money in the model, which consists of CBDC and deposits, equals 16% [of GDP] in the steady state, a number that the authors take from today's share of currency in M1. The assumption about the share of CBDC in the economy is also very high and "arbitrary" in Barrdear and Kumhof (2016/2021):

> *"As a baseline, we consider a setting in which the central bank maintains a stock of CBDC equal to 30% of GDP in steady state, backed by government debt, and potentially varied over the business cycle. Our choice of 30% is admittedly arbitrary. We have chosen it because this is an amount loosely similar to the magnitudes of QE conducted by various central banks since 2008, but we also comment on how different magnitudes would affect our results"*

In Niepelt (2023, 2) large CBDC volumes appear optimal because of social costs related to deposits (e.g. CBDC bypasses frictions in the banking sector such as deposit market power), so that "the welfare-maximizing share of CBDC in payments is generally larger than that of deposits." And depending on how CBDC is remunerated relative to deposits, replacing deposits with CBDC, either partly or fully, is "neutral" for households in the model economy of Brunnermeier and Niepelt (2019, 38) as long as the central bank refinances deposit outflows adequately.

In Gross and Letizia (2023, 5) CBDC as a share of total money would range between 5 to 25 percent for the U.S. and 1 to 20 percent for the euro area, depending on whether CBDC would be valued by agents more like cash or more like deposits. Essentially all reviewed papers predict macro-economic effects of CBDC related to significant volumes of CBDC (often translating into an increase of the total central bank money in circulation). Therefore, a low volume CBDC, like the prospective digital euro, which relies on limits, no remuneration, and a waterfall facility, would actually have no or very small effects in these models.

Financial stability implications of large volumes of CBDC

Some papers seemingly justify large-scale CBDC by assuming that the central bank can refinance banks without any adverse side-effects related to the centralization and standardization of credit allocation. Indeed, central banks would have to accept a potentially wide pool of assets from commercial banks as collateral for their lending facilities, increasing the footprint of the central bank on the economy. Moreover, refinancing all bank outflows at all times would also de facto insure all deposits and create the associated moral hazard in the banking system. Brunnermeier and Niepelt (2019) and also Keister and Sanches (2023) have considered that the central bank could simply refinance any outflows from the banking system at any time, so that banks would not be subject to liquidity stress, or so that there would not be any incentive for depositors to run in the first place. Brunnermeier and Niepelt (2019, 38) argue that CBDC decreases bank run risks and enhances financial stability:

> *"…the very act of transferring funds from bank to central bank accounts would amount to an automatic substitution of one type of bank funding (deposits held by households and firms) by another one (central bank funding for banks). By construction, a depositor run for CBDC therefore would not reduce bank funding and undermine financial stability; it would only change the composition of bank funding…. In fact, it seems plausible that the introduction of CBDC could reduce run risk rather than increasing it. After a large swap coupled with pass-through funding, the central bank would become a large, possibly the largest, depositor at private banks."*

Barddear and Kumhof (2016/2021) assume remunerated CBDC and also that CBDC is issued against government bonds, *so that bank deposits cannot be converted into CBDC*. Thereby, one of the key reasons for central banks to issue CBDC, namely to preserve the monetary hierarchy and to allow depositors to convert deposits into central bank money, is not considered. Depositors in the model cannot bank-run into CBDC by design, and the authors conclude that there are no financial stability threats of introducing large-scale remunerated CBDC. Similarly, the central bank in Assenmacher et al (2023) issues CBDC by purchasing securities in the absence of central bank reserves, excluding bank runs a priori. Another way to exclude bank runs a priori is portrayed in Piazzesi et al (2022) where

CBDC is introduced into a model world without banks. Ferrari et (2020), in turn, do not describe how agents can acquire CBDC or which implications a larger central bank balance sheet might have.

6. Predicted macro-economic consequences

Based on the design features communicated by central banks, CBDC cannot easily be differentiated in a meaningful way from cash in a macro-economic model – at least none of the papers reviewed really makes an attempt to do so (instead, e.g. it is often assumed that interest rates on CBDC can be non-zero, or that cash and CBDC is differentiated by some base utility that is not yet linked to any real macro effects etc). The balance sheet effects of CBDC and banknotes are identical for the banking system. Moreover, the emerging CBDC design choices of central banks and legislators suggest low volumes of CBDC. It is therefore difficult to imagine sizable macroeconomic effects of introducing CBDC beyond the desired positive implications for competition, innovation and stability of the monetary system – relative to the alternative scenario in which CBDC would not be issued. Also, if CBDC were to not be issued, one should assume that the growth rate of central bank money would decline to rates below nominal GDP, or even may turn negative, which would have some macroeconomic effects (inflow of cheap funding in the form of sight deposits to banks; less seigniorage income to the government, etc.).

In the case one would nevertheless assume that CBDC will increase significantly the total amount of central bank money in circulation (as many of the reviewed macro-models of CBDC do), the rise in banknotes in the euro area since 2007 could be used as an empirical robustness check for the macroeconomic implications of CBDC. Banknotes in the euro area have been growing substantially over these years of heightened uncertainty and low interest rates, and yet there do not appear (adverse) effects on the banking system and on the macroeconomy. Between 2007 and 2021, euro banknotes in circulation increased from EUR 628 billion to EUR 1572 billion, i.e. by almost one trillion euros. This increase far exceeds the amount of digital euros that is likely to be issued given the specifications of the current design. Interestingly, there is no academic literature which analyses specifically the effects of this growth of banknote volumes on the macro-economy, which is somewhat inconsistent with the fact that authors now show enormous interest in a supposed future increase of central bank money in circulation in the context of CBDC.

More recently, i.e. from 2022 to 2023, banknotes in circulation have decreased slightly in nominal terms by around EUR 5 billion in the euro area – and even more so in real terms. This trend could continue and intensify in the future, not only because of higher interest rates on bank deposits, but also due to advancing digitalization.

It is mostly the assumed sizeable share of CBDC and, more importantly, the implied increase of the total amount of central bank money in circulation described in section 5 that allows researchers to identify effects on a variety of other macroeconomic variables. According to some of the models, the introduction of CBDC increase central bank profits which are in turn shared with the government, allowing to e.g. increase public spending. Also, if CBDC replaces a significant part of deposits, the interest rate on CBDC could affect depositors' income, as well as bank profitability. Another channel of how CBDC affects the economy in the models is the increase in liquidity and efficiency in exchange which can increase output.

In Chiu et al (2019, 1), the introduction of CBDC can increase bank balance sheets through additional deposits and loans if the banking system is oligopolistic and if the central bank remunerates CBDC adequately. When calibrated to the US, and if the central bank chooses the optimal CBDC remuneration rate, then loans and deposits could increase by 1.57%.

Burlon et al. (2022) for example present a DSGE model to assess the impact of CBDC and find effects on both economic activity as well as bank lending. Regarding the effects on economic activity, they describe the following dynamics with ultimately two opposing effects on economic activity:

> *"… an increase in the amount of CBDC in circulation is associated with a decline in savers' holdings of cash and deposits. In response, banks reduce their holdings of reserves . …central bank profits soar due to an increase in its assets and a shift towards less costly liabilities. ; there is a reallocation of bank assets towards government bonds and a reallocation of bank liabilities towards central bank funding. As a consequence, bank lending margins compress, which tends to adversely affect bank lending supply and real GDP…. The increase in central bank profits exerts a downward pressure on collected taxes…, thereby promoting private consumption, economic activity, and bank lending."*

Assenmacher et al (2023) present a model without physical cash where an interest bearing CBDC is a perfect substitute for deposits. CBDC has a macro impact because its remuneration affects the spread between CBDC (and deposits) and government bond yields, where bond yields are set by central bank. Given a new monetarist structure, agents demand a certain liquidity to conduct transactions and are willing to pay a premium relative to government bonds. Assenmacher et al (2023, 4) therefore find a variety of macroeconomic effects:

> *"An increase in CBDC supply decreases the liquidity premium and boosts consumption, output, and inflation …[CBDC provision also] dampens and smoothes the reaction of investment and consumption to macroeconomic shocks"*

In Abad et al (2023) large scale adoption of CBDC affects households' optimization problem - in contrast to the similar model by Brunnermeier and Niepelt (2019) where the introduction of CBDC has no macroeconomic impact as the loss in deposits by commercial banks can be compensated by direct lending from the central bank (as discussed above). Abad et al (2023, 4) therefore also find macroeconomic effects for capital accumulation, output and consumption:

> *"In our model, the non-neutrality of CBDC is a consequence of the lower average return of households' optimal liquidity basket due to the larger share of (non-remunerated) CBDC, which entails a reduction in households' savings. The reduction in households' savings leads to a decline in investment and physical capital, which reduces output and consumption, and increases real interest rates. These effects are larger the larger the CBDC take-up is."*

Barrdear and Kumhof (2016/2021) also find sizeable effects of CBDC on financial stability as well as GDP growth:

> *"[CBDC] increases steady-state GDP by around 3%, through three channels: (i) a reduction in real interest rates, due to a reduction in the quantity of defaultable debt and its replacement by non-defaultable low-interest CBDC; 3 (ii) a reduction in distortionary taxes as a result of a lower cost of government financing; and (iii) a reduction in transaction costs due to increased liquidity throughout the economy."*

In the New Monetarist model of Keister and Sanches (2023, 417), CBDC increases the "aggregate stock of liquid assets in the economy, which promotes more efficient levels of production and exchange".

In Gross and Letizia (2023), the rise in remunerated CBDC can strengthen monetary policy pass-through, decrease bank profits and correspondingly increase central bank seigniorage. Given the potentially sizeable share of CBDC in total money holdings (up to 20 or 25 percent in the US or euro area), effects on consumption, output etc. appear likely but are not captured by the model because this part of the economy is not modelled explicitly.

Niepelt (2023) focuses on commercial bank deposits that are replaced with CBDC in a model without banknotes. But the author correctly notes in the appendix that a substitution between cash and CBDC would be "a swap of central bank liabilities without major macroeconomic consequences" (ibda p.38).

In Brunnermeier and Niepelt (2019) there are no macroeconomic consequences of CBDC because the authors assume that large-scale refinancing of deposit outflows via the central bank has no side-effects (see also section 5).

Like for most of the other papers, Fernández-Villaverde et al (2023) and Williamson (2022) also link the macro-effects of their CBDC to remuneration. Fernández-Villaverde et al (2023) consider the macroeconomic effect of CBDC relying on how the ability to pay interest on central bank money can help solving a "trilemma" of the central bank to reach a variety of policy goals. Without issuing CBDC, "the central bank can neither pay an interest rate i(n) on cash holdings nor could the central bank adjust the individual cash balances or suspend spending in a spending-contingent way. Thus, the central bank can neither attain a fully price-stable policy that requires fine-tuning i(n), nor can it "fix" the trilemma when cash is the only medium of exchange." (p. 33-34). Williamson (2022, 5) predicts that "an increase in the interest rate on CBDC causes substitution from private banking to the central bank's …. Welfare rises, as the [central bank] uses safe assets more efficiently, given the incentive

problems in private banking. As well, the increase in welfare coincides with a decline in investment and in the private capital stock."

7. Types of models into which CBDC is incorporated

We have seen that the way macroeconomists model CBDC is often subject to four different issues so that the predictions made by these models are at least not applicable to the CBDCs as outlined so far by central banks. However, the explanatory and predictive power of CBDC models depends not only per se on the way CBDC is modeled, e.g. its access policy or remuneration, but also on the model world in which CBDC is incorporated. A model environment where the central bank is able to allocate or manage credit risk in the same ways as commercial banks, or a world in which there are no commercial banks at all, may exclude certain real-world effects of different types of CBDC a priori. In other words, it is also worth taking a closer look at what kind of model environment CBDC is built into.

The model types of the fourteen papers under review almost exclusively have neoclassical roots. Gross and Letizia (2023) is an exception because it features a stock-flow consistent model in the spirit of Godley and Lavoie (2006) which is complemented with game theoretical as well as reinforcement learning elements, while, similar to the neoclassical models, also featuring money in the utility function. The other thirteen neoclassical papers can be divided into four different classes: New Monetarist Models (Assenmacher et al, 2023, Chiu et al, 2023, Jian and Zhu, 2021, Keister and Sanchez, 2023, and Williamson, 2023), New Keynesian models (Barrdear and Kumhof, 2016/2021, Piazzesi et al, 2022, Burlon et al, 2022), neoclassical models with money in the utility function (Niepelt, 2023) and Diamond and Dybvig-type models (Fernández-Villaverde et al, 2023). Moreover, combinations of these model types are possible. Abad et al (2023) and Ferrari et al (2020), for example, use a New Keynesian model with money in the utility function, and Brunnermeier and Niepelt (2019) feature financial frictions typical for New Keynesian models but also New Monetarist elements like segmented asset markets (ibid., p.30).

In the following, we will first outline the common roots of the eleven neoclassical models, focusing on the paradigms of micro-foundations and the neutrality of money. We will then see how the types of models used in the eleven CBDC papers deviate from these standard neoclassical assumptions, primarily by modelling the (central) banking sector in a more realistic way and creating room for money. While this makes these models in principle more suitable for analyzing real-world central banking topics like CBDC, a gap remains. The stock-flow consistent model of Gross and Letizia (2023) is contrasted with this.

Common roots of the thirteen neoclassical models: micro-foundations and the neutrality of money

The **paradigm of micro-foundation**s, which has grown in importance since the 1960s (King, 2008), is evident in all the CBDC papers examined. The idea is to better anchor the models and make it more likely that they will contribute to the understanding and prediction of real macroeconomic dynamics. At the center of the micro-economic foundation is the representative agent that maximizes its utility through consumption and (real) savings decisions. Put simply, an agent decides whether a coconut should be eaten or, alternatively, planted in the ground so that more coconuts can be harvested in the next period. The microeconomic foundation thus focuses on the "real" part of the economy, and less so or not at all on the financial side. Indeed, the financial sector is typically not modelled, or represented by a single agent. In this spirit, the CBDC model of Piazzesi et al (2022) features only one single agent representing the whole financial sector, not differentiating between commercial banks and the central bank. When using such a modelling environment, the effects of large-scale CBDC on financial stability can only be analyzed to a limited extent because bank runs are excluded a priori.

However, several of the CBDC models under review separate a financial sector into at least a (representative) commercial bank and a central bank (Burlon et al, 2022, Brunnermeier and Niepelt, 2019, Williamson, 2022). This separation appears necessary to understand potential side-effects of large-scale CBDC, but is not yet a sufficient condition as outlined below. Note that Abad et al (2023) and Burlon et al (2023) even go beyond the representative agent approach by modelling heterogenous banks respectively households. Brunnermeier and Niepelt (2019) also allow for possibly heterogenous firms, households and banks. Note that while Gross and Letizia (2023) feature individual agents, their model does not follow the paradigm of micro-foundations in the way as they are understood in the neoclassical macro models, but focuses on the emerging financial flows and stocks that result from agents' financial interactions.

Furthermore, not only the selection of microeconomically modeled sectors can be challenging, but also the inference of knowledge about representative agents for the logic of the whole system (fallacy of composition). In traditional macroeconomics such fallacies are already well-known, e.g. when agents try to increase (financial) savings simultaneously, the collective result can lead to the opposite (see paradox of thrift in e.g. Keynes, 1936), or might only be possible for a limited number of sectors or countries that pursue export-oriented growth strategies (see Palley, 2011, Lane and Milesi-Ferretti, 2012). Similarly, fallacies of composition can occur when using representative agents to study CBDC. In today's world, for example, central bank money is considered the safest financial asset because it does not bear any credit risk and because it has a relatively reliable real economic value, which stems from its convertibility into and scarcity compared to the book money created by the credit business

of commercial banks. From an individual perspective, it might make sense to have unlimited access to such low-risk central bank money, possibly in the form of CBDC. If, however, large-scale access to the central bank balance sheet is granted to and used by several agents, the central bank would have to accept or purchase a variety of assets and refinance banks at large scale, which could put the very basis of today's central bank money at risk. The models of Brunnermeier and Niepelt (2019) and also Keister and Sanches (2023), for example, are subject to this issue by assuming that large-scale CBDC does not alter the economic nature of central bank money.

In addition to micro-foundations, the assumption of the **neutrality of money** is also a common root of the model types used in the CBDC papers. The great moderation from the 1980s to 2007 "had inspired the view among many academic economists that the financial system was a 'veil'" (Rostagno et al, 2019, 154). As a consequence, the "savings decision" of the representative agent is typically not a financial decision, but a decision related to a single all-purpose-good. Money, banks and financial stocks and flows do not play a role[12]. This assumption appears distinct from the operational reality of a monetary economy in which financial savings in the form of commercial bank deposits, the associated lending of commercial banks, and other financial instruments play a central role in determining prices and output. Minsky (1993), Bezemer (2009), Smets et al (2010) and others have argued that a separation between real and financial savings, different types of assets and the incorporation of sectors' balance sheets are necessary for the analysis of monetary economies.

As we will see further below, CBDC models have largely moved beyond this pure version of the money neutrality by incorporating New Keynesian or New Monetarist elements like financial or informational asymmetries. However, the core of these models typically remains real in the sense that absent of such frictions, money would not matter. This stands in contrast to models like the one of Gross and Letizia (2023) which are primarily monetary in the spirit of Godley and Lavoie, 2006. Gross and Letizia (2023) start with defining the sectors' balance sheets, as well as the behavioral relationships that affect the interrelated financial flows and stocks, including banks' endogenous money creation. While stock-flow consistent models typically link money creation to economic output, and thus have an intrinsic role for money, Gross and Letizia (2023) do not focus on the real economic implications and assume that agents value different forms of money in their utility function. Minsky (1993,1) relates to both these trends, microeconomic foundations and the neutrality of money, and summarizes the paradigm of macroeconomics in the early 1990s as follows:[13]

[12] Godley and Lavoie (2006) are an exception.

[13] See also how Robert Solow, whose long-term growth models had been increasingly used for other macro questions, contested in July 2010 to the US Congress about the state of mainstream economics: "The

> *"… the dominant microeconomic paradigm is an equilibrium construct in which initial endowments of agents, preference systems, and production relations, along with maximizing behavior, determine relative prices, outputs, and an allocation of outputs to agents. Money and financial interrelations are not relevant to the determination of these equilibrium variables. The dominant macroeconomic paradigm builds upon this microeconomic paradigm, so that "real" factors determine "real" variables."*

In particular, the assumption of the neutrality of money did not necessitate a microeconomic basis for the central bank. The entire banking sector including the central bank could be neglected completely, or could be reflected in a simplified way by an exogenous growth path of the money stock. Monetary policy thus often appeared to pursue quantity targets in contrast to reality where central banks target short-term interest rates.

This fundamental way of thinking about the central bank as determining monetary aggregates also seems to carry over to a certain extent to today's CBDC models. Burlon et al (2023) feature a CBDC version that is supplied in a non-elastic way by the central bank. Similar approaches can be found in Piazzesi et al (2022) and Barrdear and Kumhof (2021).

Central bankers like Rostagno et al (2019, 62) were critical of such "mostly reduced-form or partial-equilibrium conditions linking money and prices with no clear underpinnings other than the quantity theoretic connection between money growth and inflation in the very long term." Against this backdrop, the ECB had worked on integrating a more realistic financial system into monetary macroeconomic models. Rostagno et al (2019, 154) outline that while academic New Keynesian models during the Great Moderation were typically completely "real", the ECB had internally continued to analyze money and credit developments and has integrated them into these models:

> *"[New Keynesian Models (NKM)], in its canonical specification, abstracts from financial intermediaries and relies on the existence of a complete network of deep markets … the ECB had invested financial resources and human capital in building models fully in the NKM tradition, but with a non-neutral financial sector."*

Indeed, the Christiano, Motto and Rostagno (CMR) model, developed in the early 2000s had "many types of assets in the economy that differ in their degree of liquidity and maturity" and thus give rise to portfolio decisions (Smets et al, 2010, 55). In contrast, in standard models, the role of liquidity was often neglected or insufficiently incorporated by considering an average liquidity of balance sheets respectively of single assets, instead of its distribution.

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macroeconomics that dominates serious thinking, certainly in our elite universities and in many central banks and other influential policy circles seems to have absolutely nothing to say about the problem. One single combination worker-owner-consumer-everything else simplified economy has nothing useful to say about anti-recession policy because it has built into its essentially implausible assumptions the conclusion that there is nothing for macroeconomic policy to do."

New Monetarist and New Keynesian models somewhat close the gap to real-world central banking

With the global financial crisis, such efforts towards the integration of monetary aspects have become increasingly mainstream, somewhat decreasing the gap to real-world central banking. In particular, New Monetarist and New Keynesian models have created more room for the role of money and central bank operations. Behavioral economics became also more popular after the financial crisis, questioning assumptions about rational agents, but did not make a comparably significant contribution to more realistic models of central banking.

New monetarist models assume a decentralized market and information asymmetries, so that a medium of exchange like money is needed to settle transactions (Lagos and Wright, 2005). In other words, the medium of exchange property of money improves welfare. New monetarist models thereby deviate from an earlier neoclassical approach to create room for money by assuming that money is part of the utility function of agents. Note that the latter approach is still common, for example in the CBDC models of Abad et al. (2023) and Niepelt (2023).

New monetarist models, however, attempt to go beyond this ad hoc demand for money via the utility function and provide a microeconomic foundation for the role of money by using search models.[14] Lagos and Wright (2005) model a decentralized day market where two agents can randomly (i) either exchange goods like in a barter economy, if they desire the good of the other one, or (ii) if only one of them desires the good of the other agent, agents need money to settle the exchange:

> *"Money is essential in this model for the same reason it is essential in the typical search model: since meetings in the day market are anonymous, there is no scope for trading future promises in this market, so exchange must be quid pro quo." (Lagos and Wright, 2005, 466)*

In Lagos and Wright (2005) there are no banks but an exogenous stock of money that is distributed across agents so that central bank operations as well as banks' credit provision are typically not present.

The CBDC models of Keister and Sanches (2023), Assenmacher et al (2023), Jiang and Zhu (2021) as well as Williamson (2023) all build on this New Monetarist literature.

New Keynesian models also attempt to improve monetary macro models by integrating more realistic monetary policy operations. These models did indeed close the gap with central banks' operational realities somewhat because they moved away from the vertical view of central banking by assuming that the central bank sets some sort of interest rate. In Woodford (2003), the optimal interest rate

[14] Such models were formerly prominent in labor economics. Note that matching models application to macroeconomic questions of labor markets have also been criticized because the microeconomic intuition around how workers and labor or leisure match might, once again, not be applicable on the systemic level.

depends on expected inflation and the output gap. At the same time, these models remain "real" at their core, in the sense that dynamics are determined by real fundamentals like *real* savings decisions, labor supply (Abad et al, 2023) and technology – while banks' funding needs, balance sheet compositions, *financial* investment decisions, or the institutional structure of (non)banks are typically not relevant.

A growing literature, also coming out of central banks (Christiano et al, 2007), has tried to then add short-run non-neutrality of money via different frictions to this baseline New Keynesian model. Cúrdia and Woodford (2009) introduce "heterogeneity in spending opportunities" available to different households so that credit can improve welfare.

As New Keynesian models with frictions have become the workhorse models to study central banking, it is no surprise, that many CBDC models also follow this class of models. The model of Barrdear and Kumhof (2016/2021) features sticky nominal prices and wages, while Abad et al (2023) also feature financial frictions in the form of a frictional interbank market.

Piazzesi et al (2022) also deviate from the standard New Keynesian model by trying to take money seriously, but also moves somewhat back to the vertical view on central banking:

> *"[T]he central bank sets the quantity as well as the interest rate on money, as opposed to the short rate of the representative agent's stochastic discount factor."*

During the Lehman financial crisis, the majority of central banks moved towards a so-called **floor system**, in which the banking system as a whole holds large excess reserves. Growing asset purchases (domestic and foreign) as well as related discussions around floor and corridor systems to target short-term interest rates have motivated a growing literature that further tries to improve New Keynesian models by integrating a more realistic operational framework of central banks.

Arce et al (2020), for example, discuss floor versus corridor systems in a non-standard New Keynesian model by adding an explicit banking sector as well as using the search methodology to get interbank market dynamics.

Some macroeconomic models of CBDC also try to integrate the floor system of central banks by assigning large amounts of reserves to the banking system. The banking system can then, in turn, finance large outflows of depositors who run or convert their deposits into CBDC. In Burlon et al (2023) reserves are modeled explicitly and banks can use excess reserves to finance CBDC-related deposit outflows. Abad et al (2023, 29) calibrate their CBDC model to the EA and also find that excess reserves can be used to drain a certain amount of deposit outflows:

"For a CBDC adoption level of up to 9% of GDP, the reduction in the volume of retail deposits brings about a nearly equivalent reduction in the level of excess reserves held by the banking sector…when the volume of excess reserves falls below 1% of GDP (which happens for a CBDC take-up around 8% of GDP) … banks are not 'satiated' in reserves anymore."

Finally, the way competition in the payments market is modeled affects the usefulness of the models to study the introduction of CBDC. Neoclassical models typically assume full competition, or, on the other end of the spectrum, full monopoly. As a consequence, most of the models reviewed cannot be used to study the effects of CBDC on the competitive payments landscape. Models which allow for a continuum of levels of competition are needed, as for example the model in Gross and Letizia (2023).

Implications for the reliability of the macro-predictions of the papers

The macro-predictions of the fourteen papers under review depend on the adequacy of the relevant models to study both the response of central banks to the digitization of payments and the types of CBDC considered by central banks. While the New Keynesian and New Monetarist model types have started to integrate monetary aspects and have somewhat moved away from their roots, i.e., the paradigm of the neutrality of money and the focus on "real" consumption maximizing representative agents, the financial sector may not yet be modelled in a sufficiently realistic way for the questions at hand.[15] Digitization or a relative decline in central bank money cannot or can only partially be analyzed, while other elements of the models, e.g. utility or production functions, appear less necessary. To better understand CBDCs as they are now being considered by central banks, a second generation of CBDC models that address the issues listed in this paper would be useful. The stock-flow consistent model of Gross and Letizia (2023) appears to be a good starting point because holding limits, for example, could easily be reflected in their model (as also noted by the authors).

At the same time, the models reviewed in this paper could be used to investigate and potentially confirm that the introduction of CBDC as outlined by central banks would not have any macroeconomic effects. The two-country model of Ferrari et al (2020), for example, already has a variant with a quantity-rule based CBDC, and it would be straight forward to model that foreigners are not allowed to hold domestic CBDC.

In addition, the macro papers are helpful for scenarios of other CBDC specifications that central banks might consider in the future, or for scenarios that illustrate central banks' considerations towards the current design choices. When assessing these scenarios, it seems important to point out possible limitations, such as not having room for bank runs and/or the added value of commercial banks, an

[15] This critique applies somewhat less to the Diamond and Dybvig-type model of Fernández-Villaverde et al (2023).

added value that cannot easily be replicated by a central bank.[16] In this context, the models could also be extended so that large-scale CBDC or a large-scale increase in the total amount of central bank money in circulation can have an impact on financial stability or can fundamentally change the organization of today's monetary economy through a larger central bank footprint.

8. Conclusion

The choices to be made with regards to the issuance and design of CBDC in the coming years are key for society, and central bankers and legislators need to understand what is at stake. Both will also turn to academic literature on CBDC with the legitimate expectation to find relevant predictions, also on macro-economic effects, such as to make the right policy choices. The macro-economic literature however does not appear to have paid sufficient attention to the reactive and conservative nature of CBDC issuance plans of central bank (in view of the rapid digitalization of payments), and often provides answers to key policy questions which rely on CBDC design assumptions, which do not match the ones of the actual central bank projects on CBDC (ECB, 2023a, Bank of England, 2023, PBoC, 2021). Our paper identified in particular the following gaps which future research on the macroeconomics of CBDC could consider closing.

First, the modelling in all the papers assumes that the decision to issue CBDC hits a static monetary and financial system and is not a reaction of the central bank to a changing payments environment. The decision to issue CBDC is however a "conservative" response to profound changes of the monetary system relating to digitalization, notably the lesser and lesser use (and ultimately lower stock) of banknotes. Central banks want to *preserve* the current sharing of the "market" for payments and money holdings between central bank and commercial bank money for the sake of keeping the benefits of the current co-existence of the two forms of money for consumers and merchants. While some of the papers reviewed acknowledge the reactive nature of central banks' work on CBDC and that it is more likely to stabilize the current architecture and financial accounts of the monetary system, none integrates this insight into a macro-economic model. The problem that the models turn a blind eye on the "endogeneity" of the CBDC issuance decision of central banks is a problem that is independent of the actual features of CBDC (i.e. it puts into question the predictive power of the model even if a CBDC would be designed exactly as assumed in the model).

[16] Piazzesi et al (2022) have a mode where banks provide liquidity services, however the model version that features CBDC does not have banks in it.

Second, many papers (including of those published recently) do not consider the design features of possible CBDCs as outlined more recently by central banks. Most papers assume remunerated CBDC (sometimes a static remuneration, sometimes one which would be actively varied over time for monetary policy purposes), or that CBDC is of considerable volume, and derive macroeconomic effects from that. Both assumptions are not in line with announcements made by central banks, which emphasize that CBDC will not be remunerated (as already noted by Agur et al in 2019), that CBDC holdings will be limited, that access restrictions will apply, and that features reducing incentives for pre-funding will be provided (reverse waterfall).

Third, as real-world CBDCs are expected to be unremunerated, it is difficult to specify a clear difference between CBDC and cash in macro-economic models, and indeed the papers do not develop this difference in a way that would appear solid enough to derive macro-economic consequences. Leaving aside the case of remunerated CBDC, the models seem to focus on an increase of central bank money in circulation, without this depending on whether the increase is driven by banknotes or by CBDC. Some papers rely on the idea that CBDC could have unique privacy properties (Williamson, 2022), which indeed may be a differentiation between CBDC and both cash and bank deposits, but the way this is integrated into modelling is rather specific, and there could be various other privacy-feature related effects that are not covered by the models.

Fourth, and relating to previous points, the papers generally tend to assume, in line with earlier narratives, that the issuance of CBDC will considerably increase the amount of central bank money in circulation. The declining use of banknotes, and the very prudent CBDC design as announced for example by ECB (2023a), make rather likely that the total amount of central bank money in circulation will follow a lower trend growth in the future than it did in the past. Moreover, the models who base their macroeconomic predictions on the assumed effect of CBDC to increase central bank money in circulation could be considered to not really be models of the effects of CBDC (but models describing the macroeconomic effects of a larger amount of central bank money in circulation, which could be driven equally well by an increase of banknotes).

Under the assumption of ever-progressing digitalization of society, the macro-economic effects of issuing CBDC should be identified starting from the counterfactual. If retail payments are exclusively left to the private sector and central bank money would be marginalized, then payment costs will increase (due to increasing market power of the successful firms in a market with strong network externalities), monetary and financial stability will be weakened (as the unifying convertibility test of all private moneys, i.e. to be exchangeable at sight against central bank money, will have become remote or inexistant), and strategic autonomy will be undermined with negative consequences under

scenarios of a further geopolitical deterioration. In this sense, the issuance of CBDC aims at preserving economic efficiency and stability by preserving the current role of central bank money (a genuine public good). Digitalization is generally supportive to growth and welfare. But rejecting the digitalization of an important pillar of our monetary and financial architecture (central bank money), and thus withdrawing this pillar in a scenario of a full shift of society to digital payments, would imply significant negative unintended consequences of digitalization, including of a macro-economic nature. In this sense, CBDC is simply a natural evolution of cash in a digitalized age, with structural positive effects on the economy relative to the scenario of an exit of central bank money from real economic life.

Of course, it cannot be excluded that some central banks and legislators will in the future design CBDCs which better match the assumptions taken in the macro-models reviewed. For this reason, the models remain useful for future scenarios. Moreover, macro-economic researchers could review the macro-economic predictions of the models for CBDCs designed as in ECB (2023a). Assuming a non-remunerated, low volume CBDC, what would be the macroeconomic effects predicted by the models, and what would be moreover their predictions if on top the volume of banknote in circulation would decline? For some models, volume and interest rate assumptions can be changed relatively easily, as in Gross and Letizia (2023), while others may require some redesign. At the same time, more microeconomic research appears to be necessary to understand the demand for both banknotes and CBDC (in ordinary times, in times of stress, and in times of digitization), to properly differentiate banknotes from CBDC, and to assess the impact of CBDC on the level of competition in payments.

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