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Implications of central bank digital currency for financial stability: Evidence from the global banking sector

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ABSTRACT

This study analyses the implications of central bank digital currency (CBDC) for financial stability, specifically in the banking sector. Drawing on an international database on CBDC adoption, data on 1176 banks operating in 86 countries from 2010 to 2021 were used to construct a time-varying CBDC adoption index. Our key results suggest that the adoption of CBDC contributes to financial stability. Furthermore, bank size, capitalization, operational strategy, deposit funding and domestic investment also contribute positively while loan loss reserve negatively affects bank stability. These findings are robust to a comprehensive set of tests. We further find that CBDC helps to reduce leverage and asset risks. Other evidence suggests that the adoption of CBDC can be associated with expanded lending, increased asset quality and reduced loan loss reserves. However, the impact of CBDC is only pronounced for banks of reasonable size but not for smaller banks. Moreover, CBDC adoption appears to have a more positive impact in emerging economies than in advanced economies. Finally, retail CBDC is found to promote stability, whereas wholesale CBDC hampers it. Overall, our findings have profound implications for the adoption of CBDCs and their implications for financial stability.

1. Introduction

While price and financial stability remain the core objectives of central banking across the world, the idea of adopting *central bank digital currencies* (CBDCs) has gained a lot of attention recently (Auer et al. 2022; Chiu and Keister 2022). Central banks are exploring the notion of having a CBDC; however, their stance remains very cautious (Elsayed and Nasir 2022). The principal reasons for their caution are the magnitude of the underlying task, which entails allowing households and firms to directly transact in money issued by the central bank (BOE 2020) and the possibility that CBDCs will eventually replace the existing reserve money systems. It is vital that the implications of CBDCs are well thought through so that any unintended consequences are avoided or at least minimized.

The challenge of implementing CBDCs has technological, economic, social, political, legal, environmental and ethical dimensions (Bossu et al. 2020; Carapella and Flemming 2020; Soderberg et al. 2022). Their adoption will require the appropriate technological infrastructure as well as social acceptance, and implementation will have to meet social norms and political objectives, be environmentally sustainable and adhere to ethical values. However, it is not clear how CBDC adoption can overcome these challenges. Perhaps this is why many central banks, including the Bank of England, Bank of Japan, European Central Bank, the US Federal Reserve, and the

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People's Bank of China, have been "testing the waters" and moving very cautiously toward the adoption of CBDCs (Boar and Wehrli 2021; Nabilou 2020).

Many central banks are evaluating the adoption of CBDCs in the context of their mandate on not only price stability but also economic, financial and (most recently) environmental stability (BOE 2020). The various aspects banks need to take into account in relation to the adoption of CBDCs include the transmission of monetary policy, the functioning of the banking and financial sectors, price stability, and the functioning of the labour, goods and services markets. While the adoption of digital currency by central banks is of profound importance, our understanding of the underlying challenges is very limited. This not only constrains the devising of an optimal strategy but also merits further research in its own right. Of the various aspects mentioned above, we focus here on the implications for the banking sector of the adoption of CBDCs.

As announced by the BOE (2020), if introduced in the UK, CBDCs will be denominated in pound sterling and complement cash and bank deposits rather than replace them. But how that complementary role can be performed and what implications it will have to remain open questions. The notion of extending the digital currencies' role as "*money*" is indeed stepping into the territory of public money (that held by the sovereign state) and, hence, CBDCs might be seen as an effort by central banks to claim that ground. Nevertheless, it is also stepping into the territory of private money. As a CBDC would make electronic money issued by the central bank available to all households and businesses, it would allow everyone to make electronic payments in central bank money (Agur et al. 2022). But again, the implications of such an expansion in the role of central banks to private money require further exploration.

CBDCs will also be required to contribute to the functions of central banks. A report from a group of central banks set out three principles, including "a central bank should not compromise monetary or financial stability by issuing a CBDC" (BIS 2020). But there is great uncertainty surrounding the impact of CBDCs on financial stability. The three major uncertainties concern: (i) the future structure of the financial system; (ii) the design of CBDCs and their underlying system; and (iii) the magnitude of adoption by users (BIS 2020). Whilst central banks are more stable than commercial banks and their monopoly over deposit-taking through CBDCs would be a sign of stability, the adoption of a CBDC could disrupt maturity transformation (Fernández-Villaverde et al. 2021). For this reason, an important aspect of adoption would be the underlying conditions and particularly the instability in the banking sector which may defer the date of adoption. However, there is also a good argument that regardless of the financial instability, CBDCs are emerging as the priorities of the central banks. On this aspect, Waliczek and Buonocore (2023) argued that "during periods of macroeconomic fragility, there is heightening pressure on central banks to improve economic conditions. Nevertheless, their steadfast commitment to CBDC exploration remains in place, because of the potential benefits during this turbulent period".

The influences of CBDCs on financial stability, especially banking system stability, have been recently debated, without an agreement being reached. As indicated in the literature review (section 2), a negative view of the impact of a CBDC has been taken by a variety of authors. For instance, Kumhof and Noone (2021) emphasize that the introduction of a CBDC would affect the size of banks' balance sheets, private credit, and liquidity provisions. In the case of e-krona, Juks (2018) shows that if this CBDC is not interest-bearing, it might negatively impact credit supply and financial stability. Mancini-Griffoli et al. (2018) argue that a CBDC might reduce financial stability by increasing operational risks in the payment system, financial integrity risks, and the funding costs of deposit-taking institutions. Kim and Kwon (2019), Carapella and Flemming (2020), and Fernández-Villaverde et al. (2021) agree that the introduction of a CBDC might induce a movement of deposits from private banks to the central bank's digital currency account. This would decrease the private credit supply of commercial banks, which would in turn result in higher nominal interest rates, lower those banks' reserve-deposit ratios, and lower the overall stability of the banking system (Carapella and Flemming 2020; Kim and Kwon 2019). Furthermore, Ferrari Minesso et al. (2022) caution that a CBDC might increase international linkages and thereby amplify the international spillovers of shocks. In a worst case, a CBDC might cause bank panics (Williamson 2022a).

With a more positive view, Mancini-Griffoli et al. (2018) argue that a CBDC could strengthen the benefits and reduce some of the costs and risks to the payment system, and could encourage financial inclusion. Chiu et al. (2019) added to the debate by arguing that a CBDC might have a crowding-in effect on bank credit supply, as it would enhance competition among banks, and according to Andolfatto (2020), a CBDC might have no detrimental effect on bank lending activity as competitive pressure would expand deposit funding through greater financial inclusion and desired saving. Recently, Keister and Monnet (2022) suggested that a CBDC system could reduce the maturity transformation of private banks, while making it easier for policymakers to monitor banks and detect weaknesses sooner, which would increase financial stability.

Taking a more neutral stance, Schilling et al. (2020) argue that there is a CBDC trilemma, meaning that central banks cannot achieve three goals at the same time: efficiency, financial stability, and price stability. Viñuela et al. (2020) suggest that there are trade-offs between three sets of risks: those of a cashless society, systemic bank runs and of currency substitution. According to Williamson (2022b), a CBDC would improve welfare by competing with private means of payment and shifting safe assets from the banking sector. However, Davoodalhosseini (2022) adds that CBDCs have mixed effects on welfare.

From this brief discussion, it is evident that the effects of CBDCs on financial stability overall, and on banking sector stability in particular, are not well explored. There is therefore little concrete evidence to support the arguments. Most studies have relied on simulations and theoretical models without empirical support. In this context, the present study makes a number of contributions to the debate. First, drawing on the CBDC Tracker database (see section 3), we have constructed a time-variant CBDC adoption index. Second, this study analyses the impact of CBDC adoption on banking sector stability. Third, we account for the impact of bank size, capitalization, operational strategy, deposit funding, loss provisions and domestic investment on bank stability in the context of CBDC adoption. Fourth, this study analyses the effects of CBDC adoption on the leverage, portfolio and asset risks in the banking sector as well as on bank lending. Fifth, it provides a comparative analysis between emerging and developed economies in terms of CBDC adoption. Lastly, this study also differentiates the implications of retail and wholesale CBDC and their impact on banking stability, by constructing *Retail CBDC Adoption* and Wholesale CBDC Adoption indexes that are applied to the sample countries.

Drawing on the data from 86 countries and 1176 banks from 2010 to 2021, our key results suggest that the adoption of a CBDC contributes to financial stability. Banks' size, capitalization, operational strategy, deposit funding and domestic investment also contribute positively, while loan loss reserve negatively affects banks' stability. These findings are robust to a comprehensive set of tests. CBDC also helps reduce leverage and asset risks as well as loan loss reserves. The results of additional analyses also provide some important insights. We find that CBDC adoption would contribute significantly to financial stability as it can lead to a reduction in leverage risk and asset risk. In addition, we find evidence that CBDC adoption is associated with enhanced lending opportunities, improved asset quality, and reduced loan loss reserves. However, the impact of CBDC is only pronounced for banks of reasonable size but not for smaller banks, and it has a more positive impact in emerging economies than in advanced economies. Finally, in terms of CBDC models, we find that retail CBDC can promote stability, whereas wholesale CBDC impedes it.

The rest of the paper proceeds as follows: In section 2, we critically discuss the evidence and arguments regarding the implications of CBDCs in general and for the financial sector in particular. Section 3 sets out our empirical approach while sections 4 and 5 present and discuss the results. Lastly, in section 6 we conclude and draw policy implications.

2. Literature review

The development of central bank digital currencies (CBDCs) has been a subject of great interest on the part of both scholars and economists in recent years (Auer et al. 2022). Auer et al. (2022) reviewed the literature and found that the emphasis was on (i) technologies, operation architectures, and privacy; and (ii) the macroeconomic implications for monetary policy, the financial system, and financial stability. However, there are still several unanswered questions related to CBDCs (Auer et al. 2022; Carapella and Flemming 2020; Soderberg et al. 2022). In this section, we critically review recent studies on CBDCs. Table 1 summarizes these studies. In general, there are five main strands to this literature.

In the first strand, studies focus on the development of CBDCs. For instance, Barontini and Holden (2019) surveyed the adoption of CBDCs across the globe and concluded that most central banks are still at the conceptual stages of CBDC development. Auer et al. (2020) went further and concluded that countries with higher capacity for innovation seem keen on developing CBDCs, while CBDCs in retail appear to develop in countries with a highly informal economy. Boar et al. (2020) reported that emerging market economies appear to have stronger motivations to develop CBDCs than advanced economies. Boar and Wehrli (2021) added that most central banks have no plans to issue CBDCs in the foreseeable future. However, the Covid-19 pandemic appears to have motivated central banks to set plans to develop them. While CBDCs are of great interest to policymakers, there are still challenges in issuance, such as legal constraints (Nabilou 2020).

In the second strand, studies have focused on the design of CBDCs. Two main technological designs are discussed: cash-like CBDCs and deposit-like CBDCs (Agur et al. 2022). According to Agur et al. (2022), a cash-like CBDC could lead to the disappearance of cash, while a deposit-like CBDC could depress bank credit and output. Juks (2018) discussed the case of the e-krona (the Swedish CBDC) and indicates that if the e-krona is not interest-bearing (a cash-like CBDC) its introduction could cause greater volatility in capital flows and the exchange rate, impinge on credit supply and financial stability, and negatively impact the economy. Carapella and Flemming (2020) argued that if CBDCs are deposit-like in design, they might serve as an interest-bearing substitute to commercial bank deposits.

In the third strand, the focus has been on the influence of CBDCs on monetary policy and monetary policy transmission. While Mancini-Griffoli et al. (2018) argued that a CBDC might not affect monetary policy transmission, Meaning et al. (2018) believed it could strengthen it. In the same vein, Bordo (2021) suggested that a CBDC could increase the efficiency of monetary policy, whereas Lee et al. (2021) made the case that a CBDC could be a primary tool for a future digital economy.

In the fourth strand, several studies have discussed the influences of CBDCs on financial stability, especially in the banking system. However, there is still no consensus and most of the studies made their case without empirical support. Kumhof and Noone (2021) argued that the introduction of a CBDC would affect the size of banks' balance sheets, private credit, and liquidity provisions. In the case of the e-krona, Juks (2018) argued that if this CBDC is not interest-bearing, it might negatively impact credit supply and financial stability, and similarly, Mancini-Griffoli et al. (2018) suggested that a CBDC might increase the operational risks of the payment system, financial integrity risk as well as the funding cost of deposit-taking institutions, and thereby reduce financial stability. Kim and Kwon (2019), Carapella and Flemming (2020), and Fernández-Villaverde et al. (2021) all agreed that the introduction of CBDC could lead to the withdrawal of deposits from private banks. The movement of deposits from private banks to CBDC accounts would decrease the private credit supply of commercial banks, and so result in higher nominal interest rates, lower banks' reserve-deposit ratio, and reduce bank stability (Carapella and Flemming 2020; Kim and Kwon 2019). Furthermore, Ferrari Minesso et al. (2022) have argued that a CBDC system might amplify the international spillovers of shocks and increase international linkages. In the worst case, a CBDC might cause bank panics (Williamson 2022a). In contrast, Mancini-Griffoli et al. (2018) argued that CBDC could strengthen the benefits and reduce some of the costs and risks to the payment system, and encourage financial inclusion. Chiu et al. (2019) suggested that a CBDC might have a crowding-in effect on bank credit supply as it enhances competition among banks. Andolfatto (2020) argued that a CBDC might have no detrimental effect on bank lending, as competitive pressure would expand deposit funding through greater financial inclusion and the desire to save. Keister and Monnet (2022) argued that a CBDC system could reduce the maturity transformation of private banks, while it would make it easier for policymakers to monitor and solve weak banks sooner and quicker thus CBDC would improve financial stability. Schilling et al. (2020) cautioned that there is a CBDC trilemma, where central banks cannot achieve three goals at the same time: efficiency, financial stability, and price stability. Similarly, Viñuela et al. (2020) argued that there are trade-offs between risk of a cashless society, risk of systemic bank runs, risk of currency substitution.

Lastly, a few studies have looked at other influences of CBDCs. For instance, Williamson (2022b) indicated that a CBDC would improve welfare by competing with private means of payment and shifting safe assets from the banking sector.

Table 1
Recent studies on central bank digital currencies (2018–2022).

No.	Author(s)	Focus	Approach/Method	Findings/implication
1	Juks (2018)	The case of e-krona	Discussion	If e-krona is not interest-bearing, there might be great volatility in capital flows and exchange rate If e-krona impinges on credit supply and financial stability, the economy could be negatively impacted Demand for e-krona will be relatively small from a transaction perspective
2	Mancini-Griffoli et al. (2018)	CBDC in general	Review and discussion	CBDC could strengthen the benefits and reduce some of the costs and risks to the payment system CBDC could encourage financial inclusion CBDC will face to operational risks due to disruptions and cyberattacks. CBDC might induce financial integrity riskAccount-based CBDC could increase funding costs for deposit-taking institutions (risk of financial intermediation) CBDC might have no effect on monetary policy transmission
3	Meaning et al. (2018)	CBDC in general	Discussion and theoretical modelling	CBDC can strengthen monetary policy transmissions
4	Barontini and Holden (2019)	Adoption of CBDC	Survey	Most central banks are still at the conceptual stage of CBDC
5	Chiu et al. (2019)	CBDC and private banks	Calibration based on a micro-founded general equilibrium model of payments	CBDC can enhance competition, increase deposit rates, and expand intermediation of private banks CBDC might have a crowding-in effect on bank credit supply
6	Kim and Kwon (2019)	CBDC and bank stability	A monetary general equilibrium model	Deposits in a CBDC account could decrease private credit supply => raise nominal interest rate and => lowers banks' reserve-deposit ratio. => reduce bank stability If the central bank can lend all the deposits in its CBDC account to commercial banks, CBDC can enhance financial stability through the increase of private credit supply
7	Andolfatto (2020)	CBDC and financial stability	Theoretical model combining the Diamond (1965) model of government debt with the Klein (1971) and Monti (1972) model of a monopoly bank	CBDC has no detrimental effect on bank lending activity Competitive pressure leads to a higher monopoly deposit rate which reduces profit but expands deposit funding through greater financial inclusion and desired saving. A properly designed CBDC is not likely to threaten financial stability
8	Auer et al. (2020)	CBDC development	The economic and institutional drivers of CBDC development	CBDCs are developed in countries with high capacity for innovation CBDCs in retail are developed more in countries with a highly informal economy
9	Boar et al. (2020)	CBDC development plan of central banks	Survey	There are stronger motivations in emerging market economies to develop and issue CBDCs
10	Bossu et al. (2020)	Legal aspects of CBDCs	Review and discussion	Most central bank laws do not currently authorise the issuance of CBDC to the general public.
11	Carapella and Flemming (2020)	CBDCs	Literature review	CBDC can serve as an interest-bearing substitute to commercial bank deposits => Commercial banks respond by changing deposit interest rate => funding costs => lending interest rate
12	Maniff and Wong (2020)	Benefits of CBDCs	Discussion	Technological benefits of CBDCs can be: digital form of a bearer instrument, more cost-effective payment services, greater anonymity, and a catalyst for greater innovation through programmable money.
13	Nabilou (2020)	ECB CBDC in legal perspective	Discussion	Issuing CBDC by the ECB would face a set of legal challenges
14	Schilling et al. (2020)	CBDC and targets	Discussion	The CBDC trilemma: of the three goals of efficiency, financial stability (i.e., absence of runs), and price stability, the central bank can achieve at most two
15	Viñuela et al. (2020)	CBDC trilemma	Discussion	There are trade-offs between risk of a cashless society, risk of systemic bank runs, risk of currency

(continued on next page)

Table 1 (*continued*)

No.	Author(s)	Focus	Approach/Method	Findings/implication
				substitution, and risk of economic and financial bubbles with risk of structural bank disintermediation (the CBDC dilemma).
16	Boar and Wehrli (2021)	CBDC development plans	Survey	Most central banks have no plans to issue CBDCs in the foreseeable future The Covid-19 pandemic has added new motivations to do so
17	Bordo (2021)	CBDC and monetary history	Discussion and perspective	CBDC could improve the efficiency of monetary policy
18	Chaum et al. (2021)	CBDC issuance	Discussion	If the CBDC is designed as a token-based system without distributed ledger technology, it will not affect monetary policy or financial stability
19	Fernández-Villaverde et al. (2021)	CBDC and private financial intermediaries	Discussion	CBDC would compete with private financial intermediaries for deposits. Or, the central bank, as a deposit monopolist, would attract all deposits away from the commercial banking sector
20	Kumhof and Noone (2021)	The introduction of CBDC and the balance sheet implications and digital bank run	Theoretical modelling	Introduction of a CBDC would affect the size of banks' balance sheet, private credit, and liquidity provision
21	Lee et al. (2021)	Design of CBDC	Case study of China and discussion	CBDC will be a primary tool in the future digital economy CBDC might bring comparative advantage for the country
22	Agur et al. (2022)	Design of CBDC	Discussion	CBDC can be designed as cash of deposits A deposit-like CBDC could depress bank credit and output A cash-like CBDC could lead to disappearance of cash
23	Ferrari Minesso et al. (2022)	CBDC in an open economy	A two-country DSGE model	CBDC could amplify the international spillovers of shocks and increase international linkages
24	Keister and Monnet (2022)	CBDC and financial stability	Theoretical modelling	If depositors have access to a CBDC, banks do less maturity transformation Under a CBDC system, policymakers can monitor banks and identify and resolve weaknesses sooner →CBDC would increase financial stability of the banking system
25	Williamson (2022b)	CBDC and welfare	Theoretical modelling	CBD can improve welfare by competing with private means of payment and shifting safe assets from the banking sector
26	Williamson (2022a)	CBDC and bank panics	General equilibrium model	CBDC tends to induce bank panics
28	Elsayed and Nasir (2022)	CBDC in general	Discussion	CBDCs will impact monetary policy transmission and financial stability, but our understanding is very limited.
29	Barrdear and Kumhof (2022)	CBDC and macroeconomics	A DSGE model calibrated to match the pre-2008 US	CBDC issuance can raise GDP Countercyclical CBDC policy rules can stabilize business cycles

Notes: e-krona is a Swedish central bank digital currency developed by the Riksbank (Sweden's central bank). ECB: European Central Bank.

3. Model specification and data

3.1. Measurement of bank stability

Following common practice, we used the Z-score as a proxy for bank stability (Carretta et al. 2015; Goetz 2018; Houston et al. 2010; Laeven and Levine 2009; Lambert et al. 2017). The Z-score is defined as the sum of banks' return on assets and capital to total asset ratios, standardized by the volatility of banks' return on assets. Accordingly, the Z-score for bank *i* incorporated in country *j* in year *t* is calculated as follows:

$$ZScore_{ijt} = \frac{ROA_{ijt} + Capitalization_{ijt}}{stdROA_{ijp}}$$

where *Capitalization* is the ratio of total equity capital to total assets. *ROA* is the return on assets and is calculated as the ratio of net income to total assets. *stdROA* is the bank's standard deviation of ROA calculated using three-year rolling windows, *p*.

The Z-score measures the number of standard deviations by which a bank's profitability would have to fall to wipe out the entire bank capital (Boyd and Runkle 1993; Demirgüç-Kunt and Huizinga 2009). In the other words, it measures the bank's distance to insolvency. A higher (lower) Z-score implies that a bank is at a lower (higher) risk of being insolvent and is therefore more (less) stable (Houston et al. 2010; Laeven and Levine 2009; Lambert et al. 2017). Since the Z-score is highly skewed, we follow Goetz (2018) and

Bilgin et al. (2021) and use the natural logarithm of the Z-score as the measure of bank stability.

3.2. Measurement of CBDC adoption

Data that track the trend and variations in CBDC adoption across countries have been scarce, partly because CBDCs have been attracting the attention of national authorities and economists only comparatively recently. While a number of countries have become involved in CBDC projects, the development (let alone adoption) of CBDCs is still in its early stages. In addition, given that there is much debate surrounding the economic impact of CBDCs, central bank authorities are moving cautiously (Elsayed and Nasir 2022). Wang et al. (2022) have constructed two indices, one to capture CBDC adoption intention and one to capture CBDC uncertainty based on news coverage frequency. While these indices provide some useful information regarding CBDCs' trends and variations, they produce global time series and so do not enable us to conduct a cross-sectional analysis.

The CBDC data used in this paper come from a recently established and comprehensive database, called the CBDC Tracker. It tracks and records the development and adoption of CBDCs in all countries worldwide and classifies them into four phases: i) Research (early explanatory CBDC research); ii) Proof of Concept (advanced research with a CBDC proof of concept published); iii) Pilot (CBDC has been tested in a real environment); and iv) Launched (CBDC has been officially fully launched).[1] As of December 2021, the CBDC Tracker listed a total of 84 countries and territories that had engaged in researching and adopting CBDCs to some extent, of which 56 were in the research stage, 12 were at the proof of concept, and 11 had developed and tested a CBDC in a real environment. Just 2 countries (Bahamas and Jamaica) had fully implemented CBDCs and three countries had cancelled their CBDC projects (Finland, Ecuador and Denmark).

On the basis of these stages, we constructed a time-varying CBDC adoption index across countries from 2010 to 2021: an index value of 0 indicates that a country is not involved in any stage of CDBC adoption; a value of 1 indicates a country is carrying out CBDC research; a value of 2 is given for an announcement of proof of concept; a value of 3 indicates that a country is a pilot testing a CBDC in the real environment; and a value of 4 indicates the country has fully launched its CBDC. The index is coded for the period from the date when the project was introduced. To validate this dataset, we cross-check the initial input from the CBDC Tracker against information published by the national authorities responsible for developing CBDCs.

Ideally, we would like to construct a measure that captures the design, intensity and scope of CBDC adoption in each country. However, constructing and applying such a measure on a large scale would be infeasible. One difficulty is that there is no standard definition of a CBDC. Another is that there is no international agreement on how to create CBDCs. Each country may use its own method and technology, which can make comparisons difficult. In addition, since the value of a CBDC may be based on the value of the national currency, the use and value of CBDCs may also vary from country to country. Given our objective of analysing CBDC adoption as broadly as possible, we do not attempt to capture in detail the design and scope of different stages of CBDC adoption cross-sectionally. We, therefore, constructed an index that specifically measures the stage of CBDC adoption.

3.3. Model specification

To evaluate how a CBDC affects bank stability, we use the following baseline regression model:

$$ZScore_{ijt} = \delta_0 + \delta_1 CBDCAdoption_{jt-1} + \delta_2 BankControls_{ijt-1} + MacroControls_{jt-1}$$

$$+ \tau_i + \rho_t + \varepsilon_{ijt}$$

where *i* denotes the bank, *j* denotes the country, and *t* denotes the year. The dependent variable, $ZScore_{ijt}$, is the measure of bank stability. Following the discussion in subsection 3.1, a higher (lower) value of the *ZScore* implies a higher (lower) level of bank stability.

$CBDC\ Adoption_{it-1}$ is the main independent variable of interest. It captures a country's level of CBDC adoption in a given year. It ranges from 0 for any year before an announcement by a national authority that it will be involved in CBDC projects through to 4 for countries that have fully launched a CBDC (with scores of 1, 2, and 3 respectively for exploratory CBDC research, pilot adoption, and published proof of concept). Note that *CBDC Adoption* always takes a value of 0 for countries that are not involved in any CBDC project.

We also add a vector of bank characteristics (i.e. $BankControls_{ijt-1}$) at year/t that are often considered to influence bank stability (Ahamed and Mallick 2019; Barry et al. 2011; Fang et al. 2014; Goetz 2018). It consists of bank size (*Size*), measured as the natural logarithm of total assets; capitalization level (*Capitalization*), measured as the ratio of equity to total assets; and bank deposit, measured as the ratio of deposits to total assets (*Deposits*). We also follow the literature and control for several macroeconomic factors (i.e. $MacroControls_{jt-1}$) where the banks operate. They include the natural logarithm of GDP per capita (*GDPpc*), and the ratio of fixed capital formation to GDP (*Domestic Investment*).[2] Table 2 provides detailed definitions and measurements for all variables.

It is worth noting that all right-hand-side variables are lagged by one year to mitigate endogeneity concerns in the form of reverse causality (Bilgin et al. 2021; Hasan et al. 2022). In addition, lagging the main independent variable of interest, *CBDC Adoption*, is

[1] There is also another classification: Cancelled. This status is assigned when national authorities cancel or decommission their CBDC projects. To obtain a clean sample, we exclude from our analysis countries that have cancelled/decommissioned their CBDC projects. The inclusion of those countries yields similar results (available upon request).

[2] We check the robustness of the results when incorporating additional macro-level control variables in section 4.4.

Table 2
Variable definitions and summary statistics.

Variable	Definition	Data source	N	Mean	Std.	Min	p25	p50	p75	Max
ZScore	The natural logarithm of the ratio of ROA plus capitalization divided by the standard deviation of ROA	S&P Global Market Intelligence	12,174	4.286	1.171	−3.071	3.647	4.303	4.995	11.734
CBDC Adoption	An index that captures the level of CBDC adoption in each country.	CBDC Tracker	12,174	0.278	0.573	0	0	0	0	3
Size	The natural logarithm of total assets	S&P Global Market Intelligence	12,174	15.510	2.347	11.442	13.516	15.413	17.198	21.392
Capitalization	The ratio of total equity to total assets	S&P Global Market Intelligence	12,174	0.099	0.033	0.036	0.078	0.096	0.116	0.221
Interest Income	The ratio of interest income to total income	S&P Global Market Intelligence	12,174	0.554	0.188	0.248	0.430	0.522	0.760	0.922
Deposits	The ratio of total deposits to total assets	S&P Global Market Intelligence	12,174	0.766	0.126	0.287	0.707	0.802	0.857	0.930
LLR	The ratio of loan loss reserve to total loans	S&P Global Market Intelligence	12,174	2.215	2.297	0.240	1.014	1.391	2.520	14.417
Domestic Investment	The ratio of gross fixed capital formation to GDP	World Development Indicators (WDI)	12,174	0.226	0.056	0.140	0.198	0.208	0.238	0.439
GDPpc	Natural logarithm of GDP per capita	World Development Indicators (WDI)	12,174	10.296	1.066	7.275	9.814	10.817	10.969	11.354

Note: This table reports the definitions and summary statistics of the variables used in main regression tests. The sample consists of 12,174 bank-year observations based on the data sourced from CBDC Tracker, S&P Global Market Intelligence and World Development for the period from 2010 to 2021. Variables are winsorized at the 1st and 99th percentiles. The number of observations (N), means (Mean), standard deviations (Std.), minimum (Min), 25th percentiles (p25), medians (p50), 75th percentiles (p75), and maximum (Max) are reported.

important as an immediate impact of the adoption of CBDC is not necessarily expected. We also include bank fixed effects (τ_i) and year fixed effects (ρ_t) to alleviate the potential problem of omitted variables (González 2022). The inclusion of these fixed effects enables us to control for unobserved bank-specific factors and the time-specific effects that are common to all banks in the sample. ε_{ijt} indicates unobserved error terms. Following White (1980), we use cross-sectional standard errors and covariance (corrected for degrees of freedom) are used to mitigate the impact of heteroscedasticity.

3.4. Data and sample selection

We obtain the data for this study from several sources. We start our sample construction with the 1,306 publicly listed banks that have financial data from the S&P Global Market Intelligence database for the period 2010 to 2021. We start in 2010 to avoid the impact of any confounding events (for example, the global financial crisis) on our empirical analysis and because Bitcoin and other cryptocurrencies appeared only after 2008/2009. Our sample period ends in 2021 because this is the latest year for which bank and macro-level data are available. We exclude investment banks and private banks because they have different balance sheets and income structures (Davis et al. 2022).

Second, as mentioned above, the main independent variable, *CBDC Adoption*, is manually derived from the CBDC Tracker, which provides an up-to-date record of CBDC adoption for all countries around the world. Finally, data on country-level economic factors such as GDP and domestic investment are retrieved from the World Development Indicators database provided by the World Bank for the same period (2010 to 2021).

As is common in the literature, we winsorize all right-hand-side variables at the 1 % level on both tails to mitigate the impact of outliers. The final sample comprises 1,175 publicly listed commercial banks operating in 86 countries. Using a global country sample enables us to assess the general impact of CBDC adoption.

4. Empirical results

4.1. Summary statistics

Table 2 shows the summary statistics for the entire sample. The main variable of interest is bank stability, measured as the natural logarithm of the Z-score. As shown in Table 2, its mean value is 4.286. The mean value of *CBDC Adoption* is 0.278, indicating that the adoption of CBDC is still in its early stages worldwide.

Banks in the sample have an average size (*Size*), which is proxied as the natural logarithm of total assets, of 15.510. On average, equity capital (*Capitalization*) and total deposits (*Deposits*) account for 9.9 % and 76.6 % of total assets, respectively. The average ratio of interest income to total income (*Interest Income*) is around 0.55. The average ratio of loan loss reserves to total loans (*LLR*) is 0.226. On average, gross fixed capital formation is 22.6 % of GDP. Finally, an average country has $42,182 in GDP per capita, which translates to 10.296 when taking the natural logarithm of GDP per capita (*GDPpc*) to smooth out the skewed distribution of economy size for analysis.

4.2. Correlations

Table 3 presents the Person correlation coefficients for the main variables. Bank stability, proxied by the natural logarithm of the Z-score, is positively correlated with *CBDC Adoption*. This implies a positive association between CBDC adoption and bank stability. In addition, it appears that larger banks and banks with a higher share of interest income in total income are more stable. Similarly, the bank deposits variable is also positively correlated with bank stability. By contrast, banks with a higher share of loan loss reserves in total loans seem to be less stable. In terms of macroeconomic variables, *Domestic Investment*, and *GDPpc* both show a positive correlation with *CBDC Adoption*.

Table 3
Correlation matrix.

		1	2	3	4	5	6	7	8	9	VIF
1	*ZScore*	1									
2	*CBDC Adoption*	−0.001*	1								1.13
3	*Size*	0.042*	0.240*	1							1.85
4	*Capitalization*	0.017	−0.120*	−0.268*	1						1.28
5	*Interest Income*	0.148*	0.007*	−0.410*	0.111*	1					3.00
6	*Deposits*	0.059*	−0.058*	−0.527*	−0.076*	0.561*	1				2.07
7	*LLR*	−0.304*	−0.009	0.156*	0.142*	−0.368*	−0.272*	1			1.43
8	*Domestic Investment*	0.094*	0.221*	0.388*	−0.204*	−0.446*	−0.194*	0.005	1		1.64
9	*GDPpc*	0.114*	0.009	−0.340*	−0.012	0.709*	0.308*	−0.458*	−0.468*	1	1.81

Note: This table presents the correlation matrix of the variables used in Model 1 for analysing the impact of CBDC adoption on bank stability. *ZScore* is defined as (ROA + Capitalization)/Standard deviation of ROA. *CBDC Adoption* is an index that captures the level of CBDC adoption in each country. Detailed definitions of all variables are in Table 2. * indicates significance levels at the 10 %,

Table 4
Impact of CBDC on bank stability.

	ZScore	*ZScore*	*ZScore*
	(1)	(2)	(3)
CBDC Adoption	**0.237*****	**0.119*****	**0.107*****
	(0.026)	**(0.026)**	**(0.026)**
Size	0.092***	0.477***	0.156***
	(0.006)	(0.105)	(0.054)
Capitalization	3.019***	4.196***	4.933***
	(0.429)	(0.761)	(0.749)
Interest Income	0.570***	1.117***	1.127***
	(0.078)	(0.175)	(0.157)
Deposits	0.714***	1.650***	0.586**
	(0.142)	(0.356)	(0.228)
LLR	−0.147***	−0.099***	−0.104***
	(0.006)	(0.011)	(0.011)
Domestic Investment			2.025***
			(0.727)
GDPpc			−0.122
			(0.108)
Constant	1.884***	−5.385***	1.116
	(0.182)	(1.855)	(1.040)
Observations	12,174	12,174	12,174
R-squared	0.129	0.482	0.483
Year FE	NO	YES	YES
Bank FEs	YES	YES	YES

Note: This table presents the results of the baseline model for analysing the impact of CBDC adoption on bank stability. The regression models are based on a sample of 12,174 observations of 1,175 publicly listed commercial banks in 86 countries. The dependent variable is the natural logarithm of the Z-score, defined as (ROA + Capitalization)/Standard deviation of ROA. The main independent variable of interest is *CBDC Adoption*, which is an index that captures the level of CBDC adoption in each country. Detailed definitions of all variables are in Table 2. Bank and year fixed effects are controlled in most of the models. Robust standard errors are in parentheses. *,**, and *** indicate significance levels at the 10 %, 5 %, and 1 %, respectively.

Overall, the correlations among the control variables are small. The highest correlation coefficient is 0.709, between bank interest income (*Interest Income*) and GDP per capita (*GDPpc*). Multicollinearity is tested through the variance inflation factor (VIF), and all the values are well below 5, which suggests that our analysis is not affected by multicollinearity issues.

4.3. Baseline result: CBDC and bank stability

Table 4 presents the estimations with robust standard errors examining the impact of CBDC adoption on bank stability. Across all the models, the dependent variables are the natural logarithm of the Z-score, which enables us to interpret the coefficients as percentages (Meuleman and Vander Vennet 2020). Column (1) shows the results obtained from estimating a basic model with bank control variables and bank fixed effects to control for unobserved bank heterogeneity. In Column (2), we add year-fixed effects. Column (3) presents the results of the specification when some time-varying country-level controls are included along with bank-level control variables and both bank and year-fixed effects.

Overall, we find that in all regressions, the estimated coefficients on *CBDC Adoption* are positive and statistically significant, indicating that the adoption of CBDC is associated with a higher level of bank stability. For the sake of interpretation, we take Column (3) to be our main specification. Since we use the natural logarithm of the Z-score, the coefficients can be interpreted as semi-elasticity. The result shows that a one standard deviation increase in the index of CBDC adoption (i.e. 0.573), corresponds to a more mature development and adoption of CBDC, is associated with an increased bank stability (i.e. *ZSscore*) of approximately 6.1 % = (0.107*0.573). This result is consistent with the perception that CBDCs can enhance financial stability by increasing the resilience, efficiency and transparency of the financial system and reducing the incidence of bank runs (Soderberg et al. 2022).

As regards the impact of control variables, our findings suggest that larger banks are associated with higher levels of stability. This result corroborates the view that large banks are more financially stable due to their more efficient use of risk tools and greater diversification (Demirgüç-Kunt and Huizinga 2010; Fang et al. 2014). Next, bank capitalization, as measured by the ratio of total equity to total assets, is also positively and significantly related to bank stability, possibly because a higher level of capitalization reflects a greater ability of banks to absorb risk (Bhattacharya and Thakor 1993; Repullo 2004). In a similar vein, a higher ratio of interest income to total income, which captures banks' profitability from traditional interest-bearing activities, is found to be positively associated with bank stability. This is consistent with the view that traditional banking activities are more stable over time (Bilgin et al. 2021). Likewise, banks that attract more deposit funding (indicated by a higher deposit-to-asset ratio) appear to be more stable. By contrast, loan loss reserve, which is a proxy for ex-ante credit risk, is negatively associated with financial stability, consistent with the literature (Ahamed and Mallick 2019; Fang et al. 2014). Regarding the macroeconomic controls, a higher level of domestic investment is observed to be beneficial for bank stability.

4.4. Robustness tests

To test the sensitivity of our main results, we conduct a number of robustness checks. The results are presented in Table 5.

In the first set of these tests, we re-estimate our baseline model using different model specifications. Specifically, in Column 1, we retain year fixed effects and replace bank fixed effects with country fixed effects in order to control for the average impact of unobservable time-invariant differences across countries. In Column 2, we add regional fixed effects and year-fixed effects to control for time-invariant region-specific factors. In Column 3, we use region-year fixed effects to absorb all variables that do not vary across banks within a given region and year. In all these columns, the estimated coefficients on *CBDC Adoption* are positive and statistically significant, in line with the baseline results.

Next, given that the adoption of CBDC happens at the country level, in Column 4 we cluster standard errors at the country level. This approach enables us to take into account any potential time-varying correlations in unobserved factors that affect different banks within the same country (Ahamed and Mallick 2019; Petersen 2008)). The result is consistent with the main result.

In Column 5, instead of clustering the standard errors at the country level, we cluster them at the bank level (Goetz 2018; Köhler 2015). This is because some countries in the sample have more observations than others, and a small number of clusters might generate estimation bias (Bourveau et al. 2018). The signs and magnitudes of the coefficients of interest remain unchanged.

In Column 6, we use an alternative measure of CBDC adoption. Central banks' cautious approach to the adoption of CBDCs may not have a detectable impact on bank stability. To mitigate this concern, in this robustness test, we replace our CBDC adoption index with a binary variable indicating if a CBDC has actually been introduced. That is, we construct a dummy variable which equals one if a country has tested a CBDC in the real environment (i.e. Pilot) or fully launched a CBDC, and zero otherwise (i.e. the country is not involved in any CBDC project at all, or is only at the research stage). The result is in line with the baseline result.

We also re-estimate the baseline model using an amended version of our dependent variable (i.e. *ZScore*). In Column 7, we construct an alternative *ZScore* by requiring a longer time window (i.e. five years) when calculating the standard deviation of asset returns (Anginer et al. 2014). That is, we calculate the Z-score as bank return on assets (i.e. ROA) plus bank equity to asset ratio, scaled by the standard deviation of asset returns over a five-year rolling window. The result still holds.

One may also be concerned that the health and economic crisis due to the Covid-19 pandemic, which began in 2019, may produce noise that affects our results. In Column 8, we mitigate this concern by excluding the period from 2019 to 2021 from our analysis. The result is consistent with the main result.

Next, we follow the common practice in the empirical economic literature and re-estimate the baseline model using the two-step system generalized method of moments (GMM) estimator (Altunbas et al. 2018; Cerutti et al. 2017). The advantage of the two-step system GMM estimator is that, instead of depending on external instruments or natural experiments, which are often difficult to

Table 5
Robustness tests.

	Alternative Fixed Effects: Country FEs and Year FEs	Alternative Fixed Effects: Regional FEs and Year FEs	Alternative Fixed Effects: Regional-Year FEs	Cluster Standard Error (Country-level)	Cluster Standard Error (Bank-level)	Alternative Measure of CBDC Adoption	Alternative Measure of Z-Score	Exclude Covid-19 Period	Two-step system GMM estimator
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
CBDC Adoption	**0.113*****	**0.160*****	**0.127*****	**0.107***	**0.107*****	**0.174****	**0.080*****	**0.248*****	**0.184*****
	(0.028)	**(0.027)**	**(0.027)**	**(0.056)**	**(0.035)**	**(0.087)**	**(0.021)**	**(0.045)**	**(0.031)**
$ZScore_{t-1}$									0.487***
									(0.079)
Other Controls	YES	YES	YES	YES	YES	YES	YES	YES	YES
Observations	12,174	12,174	12,174	12,174	12,174	12,174	12,174	9,905	11,002
R-squared	0.207	0.157	0.176	0.483	0.483	0.483	0.634	0.531	–
Year FEs	YES	YES	NO	YES	YES	YES	YES	YES	YES
Country FEs	YES	NO	NO	NO	NO	NO	NO	NO	NO
Regional FEs	NO	YES	NO	NO	NO	NO	NO	NO	NO
Regional-Year FEs	NO	NO	YES	NO	NO	NO	NO	NO	NO
Bank FEs	NO	NO	NO	YES	YES	YES	YES	YES	NO

Note: This table presents the results of the baseline model for analysing the impact of CBDC adoption on bank stability using several robustness tests. Column 1 includes country and year fixed effects. Column 2 includes regional and year fixed effects. Column 3 includes regional-year fixed effects. In column 4, standard errors are clustered at the country level, while in Column 5, standard errors are clustered at the bank level. Column 6 reports result when an alternative measure of CBDC is employed. Column 7 uses an alternative measure of the Z-score. Column 8 excludes the Covid period (i.e. 2020 to 2021) from the analysis. Column 9 shows the result of the two-step system GMM estimator. Across all the models, the dependent variable, unless otherwise stated, is the natural logarithm of *ZScore* and is defined as (ROA + Capitalization)/Standard deviation of ROA. The main independent variable of interest is *CBDC Adoption*, which is an index that captures the level of CBDC adoption in each country. Detailed definitions of all variables are in Table 2. Bank and year fixed effects are controlled in most of the models. Robust standard errors are in parentheses. *, **, and *** indicate significance levels at the 10 %, 5 %, and 1 %, respectively.

Table 6
DiD Result – The pilot adoption of CBDC in China.

	ZScore	*ZScore*
	(1)	(2)
Pilot CBDC	0.203**	0.215***
	(0.082)	(0.083)
Size	0.088***	0.075***
	(0.025)	(0.023)
Capitalization	−0.127	−1.508
	(2.315)	(2.108)
Interest Income	0.019	0.012
	(0.483)	(0.585)
Deposits	1.329***	1.067*
	(0.445)	(0.550)
LLR	−0.001	−0.039
	(0.044)	(0.055)
Constant	2.518***	2.680***
	(0.587)	(0.556)
Year FE	YES	YES
Bank FEs	YES	YES
Observations	524	524
R-squared	0.186	0.39

Note: This table presents the results of the DiD model for analysing the impact of CBDC adoption on bank stability in China. The dependent variable is the natural logarithm of the Z-score, defined as (ROA + Capitalization)/Standard deviation of ROA. The main independent variable of interest is the DiD term - *Pilot CBDC*. It is a dummy that equals one if a bank incorporated in province that experience the adoption of CBDC in a given year, and zero otherwise. Definitions of all variables are in Table 2. Robust standard errors are in parentheses. *,**, and *** indicate significance levels at the 10 %, 5 %, and 1 %, respectively.

identify, it uses an internal instrument through an appropriate adoption of lag length to address endogeneity concerns (Ullah et al. 2018). This method is appropriate given the "small *T* and large *N*" nature of our study. Column 9 of Table 5 reports the result of the two-step system GMM model. We find a positive and statistically significant coefficient on *CBDC Adoption*, supporting a robust association between CBDC adoption and bank stability.

4.5. The pilot adoption of CBDC in China – DiD results

One may be concerned that since CBDC adoption is still in its early stages, it is difficult to assess the real impact of CBDC. To mitigate this concern and further reduce the potential endogeneity issue, we exploit the pilot adoption of CBDC in some cities in China as a quasi-natural experiment. From 2020 to 2022, twenty-three Chinese cities were sequentially added to the pilot CBDC adoption program in China. Specifically, in 2020, three cities were selected to participate in the pilot program, including Shenzhen, Suzhou and Chengdu, followed by four more cities in 2021 (Shanghai, Hainan, Changsha, and Xi'an). In 2022, thirteen other cities were added to the pilot CBDC adoption program, including Qingdao, Dalian, Beijing, Tianjin, Chongqing, Guangzhou, Fuzhou, Xiamen, Hangzhou, Ningbo, and Wenzhou. The pilot adoption of CBDC was staggered across both time and jurisdictions, and more importantly, the decisions of pilot CBDC adoption had no apparent relation to individual banks' performance or stability, thus allowing us to reduce potential endogeneity concerns. Arguably, this constitutes a natural experiment for the purposes of this study. To this end, our staggered difference-in-difference model is specified as follows:

$$ZScore_{ict} = \gamma_0 + \gamma_1 PilotCBDC_{ct} + \gamma_2 BankControls_{ict-1} + \tau_i + \rho_t + \varepsilon_{ict} \quad (2)$$

Where *i*, *c*, and *t* denote bank, city, and year, respectively. Z-Score is the measure of bank stability described in Section 3.1. Our key variable of interest is the dummy variable *Pilot CBDC*. It equals one if bank i incorporated in city c experiences the pilot adoption of Pilot CBDC in year t and zero otherwise. A positive (negative) and significant coefficient on Pilot CBDC would indicate that the adoption of CBDC facilitates (or hinders) bank stability.

We also incorporate into the model the same set of bank controls as in the baseline model (1). τ_i and ρ_t are bank and year fixed effects, respectively. Standard errors are clustered at the city level. The result of model (2) is presented in Table 6. Column (1) shows the results when we include bank-fixed effects, whereas in Column (2) both bank and year-fixed effects are incorporated.

Overall, we find that in both regressions, the estimated coefficients of *Pilot CBDC* are positive and statistically significant. Thus, it lends support to the baseline finding that CBDC contributes to promoting bank stability.[3]

[3] We also conduct a test to assess the parallel trend assumption as well as several falsification tests to ensure the exogeneity of the shock (i.e., pilot adoption of CBDC) and the validity of the DiD model. The test results are available upon request.

Table 7
CBDC and leverage risk, portfolio risk, and asset risk.

	Leverage Risk	Portfolio Risk	Asset Risk
	(1)	(2)	(3)
CBDC Adoption	**−0.121*****	**−0.010**	**−0.001*****
	(0.026)	**(0.030)**	**(0.000)**
Size	−0.176***	0.270***	−0.003***
	(0.054)	(0.057)	(0.001)
Capitalization	−5.167***	−0.235	−0.030*
	(0.744)	(0.900)	(0.017)
Interest Income	−1.033***	1.602***	−0.006***
	(0.155)	(0.191)	(0.002)
Deposits	−0.687***	0.944***	−0.017***
	(0.237)	(0.275)	(0.004)
LLR	0.080***	−0.122***	0.001***
	(0.011)	(0.015)	(0.000)
Domestic Investment	−1.615**	4.710***	0.003
	(0.706)	(0.929)	(0.009)
GDPpc	0.246**	−0.105	0.006***
	(0.111)	(0.127)	(0.002)
Constant	−2.016*	−4.027***	0.008
	(1.070)	(1.215)	(0.014)
Observations	12,237	11,634	12,252
R-squared	0.486	0.445	0.451
Year FE	YES	YES	YES
Bank FEs	YES	YES	YES

Note: This table presents the results of the models for analysing the impact of CBDC adoption on leverage risk, portfolio risk, and asset risk. Leverage risk is measured as the negative of the natural logarithm of the ratio of capitalization to standard deviation of ROA. Portfolio risk is measured as the negative of the natural logarithm of the ratio of ROA to standard deviation of ROA. Finally, asset risk is the standard deviation of ROA. The main independent variable of interest is *CBDC Adoption*, which is an index that captures the level of CBDC adoption in each country. Detailed definitions of all variables are in Table 2. Bank and year fixed effects are controlled in all of the models. Robust standard errors are in parentheses. *,**, and *** indicate significance levels at the 10%, 5%, and 1%, respectively.

5. Additional analyses

5.1. CBDC and leverage risk, portfolio risk, and asset risk

To gain a deeper understanding of how the adoption of CBDC affects bank stability, we decompose the Z-score into its three components and explore how CBDC influences leverage risk, portfolio risk, and asset risk (Bilgin et al. 2021; Köhler 2015). *Leverage Risk* is measured as the negative of the natural logarithm of the ratio of capitalization to standard deviation of ROA. *Portfolio Risk* is measured as the negative of the natural logarithm of the ratio of ROA to the standard deviation of ROA. Finally, *Asset Risk* is the standard deviation of ROA. We then amend our baseline model (Equation 1) by sequentially replacing the dependent variable, *ZScore*, with *Leverage Risk*, *Portfolio Risk* and *Asset Risk*.

Table 7 provides the regression results of the augmented models to assess the impact of CBDC adoption on leverage risk (Column 1), portfolio risk (Column 2), and asset risk (Column 3). Overall, the estimated coefficients on *CBDC Adoption* are statistically significant and negative in Columns 1 and 3. These results imply that the adoption of CBDC significantly reduces leverage risk and asset risk. In terms of portfolio risk, the estimated coefficient on *CBDC Adoption* is also negative but not statistically significant (Column 2). Taken together, these findings illustrate that the improvement of overall financial stability is not driven by portfolio risk but by the reduction of leverage risk and asset risk.

5.2. CBDC, bank lending, loan performance, and loan loss reserves

So far, we have documented that the adoption of CBDC shapes the safety and soundness of banks. In this section, we attempt to investigate the channels through which CBDC adoption might affect bank stability. In general terms, the channels through which banks become more financially stable are by increasing their lending (and thus benefiting from more stable traditional interest-bearing activities), improving loan quality and by lowering credit risk.

To test this proposition, we augment the baseline model (1) and sequentially replace the dependent variable, *ZScore*, with *Total Loans*, *Non-Performing Loans*, and *LLR*. *Total Loans* are measured as the ratio of total loans to total assets. *Non-Performing Loans* is the ratio of total non-performing loans to total loans, whereas *LLR* is the ratio of total loan loss reserves to total loans. The results of this augmented model are reported in Table 8. In line with our expectations, the adoption of CBDC is associated with increased lending (Column 1) and reduced loan loss reserves (Column 3). Interestingly, as shown in Column (2), we find that asset quality increases (as the level of nonperforming assets decreases) after the adoption of CBDC. These findings suggest that the improvement of overall financial stability is driven by expanded interest-bearing activities, increased asset quality, and reduced ex-ante credit risk.

Table 8
CBDC, bank lending and loan performance.

	Total Loans	NPA/Loan	LLR
	(1)	(2)	(3)
CBDC Adoption	**0.010*****	**−0.002****	**−0.001*****
	(0.002)	**(0.001)**	**(0.000)**
Size	−0.002	0.008***	0.001***
	(0.004)	(0.001)	(0.000)
Capitalization	0.009	0.041***	0.000
	(0.047)	(0.015)	(0.004)
Interest Income	0.027**	−0.059***	−0.019***
	(0.012)	(0.004)	(0.001)
Deposits	0.097***	−0.021***	−0.010***
	(0.022)	(0.005)	(0.002)
LLR	−0.009***	0.012***	0.007***
	(0.001)	(0.000)	(0.000)
Domestic Investment	0.059	−0.174***	−0.060***
	(0.057)	(0.017)	(0.005)
GDPpc	0.109***	−0.008***	−0.001
	(0.008)	(0.003)	(0.001)
Constant	−0.562***	0.061**	0.027***
	(0.081)	(0.025)	(0.008)
Observations	12,234	10,549	12,226
R-squared	0.854	0.813	0.921
Year FE	YES	YES	YES
Bank FEs	YES	YES	YES

Note: This table presents the results of the models for analysing the impact of CBDC adoption on bank lending, loan performance, and loan loss reserves. Bank lending is measured as the ratio of total loans to total assets. Loan performance is measured as the ratio of total non-performing loans to total loans. Finally, loan loss reserves is the ratio of total loan loss reserves to total loans. The main independent variable of interest is *CBDC Adoption*, which is an index that captures the level of CBDC adoption in each country. All regressions include control variables (see Table 2), bank fixed effects and year fixed effects. Robust standard errors are in parentheses. *, **, and *** indicate significance levels at the 10%, 5%, and 1%, respectively.

5.3. *CBDC adoption and cross-sectional variation in bank stability*

We next explore bank-level heterogeneity by focusing on specific bank characteristics. Given that larger banks might be better able to manage the challenges associated with CBDCs and have sufficient resources to develop the necessary infrastructure and systems needed, we expect that the adoption of a CBDC would have a more prominent impact on the financial stability of larger banks. In contrast, small banks may not have the same capabilities or be able to absorb the risks associated with the use of CBDCs. This could lead to them becoming less competitive and even go out of business.

To see whether CBDC adoption has different effects on banks of different size, in Table 9 we divide the full sample into terciles by bank size, measured as the natural logarithm of total assets. The estimated coefficients on *CBDC Adoption* are positive and significant for large banks (Column 1) and medium-size banks (Column 2), but that for small banks is not statistically significant (Column 3). These results provide support for our propositions. Only banks of reasonable size are affected and become more financially stable following the adoption of CBDC, while smaller banks are not.

5.4. *CBDC adoption in advanced economies and emerging markets and developing economies*

We further test the impact of CBDC adoption on bank stability in advanced economies and emerging markets and developing economies (EMDEs). We expect that CBDCs will have a more positive impact in emerging economies than in advanced economies. EMDEs typically have less efficient payment systems and less transparent financial systems than advanced economies. Therefore, in EMDEs there is greater scope for the adoption of CBDCs to improve the efficiency of the payments system, that is, to increase the speed and security of transactions. In addition, it could improve transparency, and thereby build greater levels of trust in the financial system. In contrast, given the maturity, efficiency and transparency of the financial system of advanced economies, CBDCs may have a more limited impact on bank stability.

To test our prediction, we divide the full sample into two sub-samples by the level of economic development and present the results in Table 10. Column 1 reports the results for advanced economies, whereas Column 2 shows the result for EMDEs. The estimated coefficient on *CBDC Adoption* for advanced economies is not statistically significant, while that for EMDEs is positive and significant. These results are in line with our proposition that the benefits of CBDCs are likely to be more significant in EMDEs than in advanced economies.

5.5. *Retail CBDC versus wholesale CBDC*

CBDCs can be categorized as retail CBDCs or wholesale CBDCs. Retail CBDCs are designed to be used by the general public (i.e.

Table 9
Impact of CBDC across banks of different size.

	Large Bank	Medium Bank	Small Bank
	(1)	(2)	(3)
CBDC Adoption	**0.108*****	**0.160****	**0.001**
	(0.031)	**(0.067)**	**(0.276)**
Size	0.116	0.145*	0.323***
	(0.133)	(0.077)	(0.097)
Capitalization	5.177***	3.083***	6.868***
	(1.683)	(1.168)	(1.299)
Interest Income	1.044***	1.260***	1.712***
	(0.224)	(0.292)	(0.400)
Deposits	1.100***	0.398	0.473
	(0.366)	(0.381)	(0.461)
LLR	−0.099***	−0.069***	−0.258***
	(0.014)	(0.020)	(0.030)
Domestic Investment	1.364	3.609***	−6.480**
	(0.936)	(1.285)	(2.774)
GDPpc	−0.067	−0.550***	−0.550
	(0.173)	(0.212)	(0.663)
Constant	0.910	5.434***	5.287
	(1.793)	(2.064)	(7.141)
Observations	4,039	4,150	3,937
R-squared	0.517	0.482	0.529
Year FE	YES	YES	YES
Bank FEs	YES	YES	YES

Note: This table presents the results of the models for analysing the impact of CBDC adoption across banks. The full sample is divided into terciles by bank size, measured as the natural logarithm of total assets. The results of the models for large banks, medium-size banks, and small banks are presented in Column 1,2 and 3, respectively. Across all the models, the dependent variable is the natural logarithm of the Z-score, defined as (ROA + Capitalization)/Standard deviation of ROA. The main independent variable of interest is *CBDC Adoption*, which is an index that captures the level of CBDC adoption in each country. Detailed definitions of all variables are in Table 2. Bank and year fixed effects are controlled in all of the models. Robust standard errors are in parentheses. *,**, and *** indicate significance levels at the 10 %, 5 %, and 1 %, respectively.

Table 10
CBDC adoption and bank stability - Advanced vs emerging and developing countries.

	Advanced Economies	EMDEs
	(1)	(2)
CBDC Adoption	−0.021	0.084**
	(0.048)	(0.034)
Size	0.132**	0.260**
	(0.053)	(0.126)
Capitalization	4.947***	4.926***
	(0.908)	(1.311)
Interest Income	1.234***	0.382
	(0.218)	(0.257)
Deposits	0.156	1.607***
	(0.292)	(0.346)
LLR	−0.164***	−0.081***
	(0.020)	(0.014)
Domestic Investment	−1.801	5.032***
	(1.242)	(0.936)
GDPpc	−0.752***	0.266
	(0.182)	(0.174)
Constant	9.597***	−5.497***
	(1.862)	(1.598)
Observations	8,895	3,279
R-squared	0.499	0.455
Year FE	YES	YES
Bank FEs	YES	YES

Note: This table presents the results of the models for analysing the impact CBDC on bank stability in advanced economies (column 1) and emerging and developing countries (column 2). The dependent variable is the natural logarithm of ZScore and is defined as (ROA + Capitalization)/Standard deviation of ROA. In Column 1, the main independent variable of interest is *Retail CBDC Adoption*, which is an index that captures the level of retail CBDC adoption in each country. In Column 2, the main independent variable of interest is *Wholesale CBDC Adoption*, which is an index that captures the level of wholesale CBDC adoption in each country. Detailed definitions of all variables are in Table 2. Bank and year fixed effects are controlled in most of the models. Robust standard errors are in parentheses. *,**, and *** indicate significance levels at the 10 %, 5 %, and 1 %, respectively.

Table 11
Retail CBDC vs Wholesale CBDC.

	Retail CBDC	Wholesale CBDC
	(1)	(2)
Retail CBDC	0.192***	
	(0.028)	
Wholesale CBDC		−0.126***
		(0.035)
Size	0.161***	0.153***
	(0.054)	(0.054)
Capitalization	4.979***	5.004***
	(0.748)	(0.749)
Interest Income	1.163***	1.068***
	(0.157)	(0.156)
Deposits	0.612***	0.529**
	(0.227)	(0.227)
LLR	−0.105***	−0.106***
	(0.011)	(0.011)
Domestic Investment	1.710**	1.415*
	(0.720)	(0.731)
GDPpc	−0.169	−0.182*
	(0.108)	(0.110)
Constant	0.192***	
	(0.028)	
Observations	12,174	12,174
R-squared	0.484	0.483
Year FE	YES	YES
Bank FEs	YES	YES

Note: This table presents the results of the models for analysing the impact of retail and wholesale CBDCs on bank stability. The regression models are based on a sample of 12,174 observations of 1,175 publicly listed commercial banks in 86 countries. The dependent variable is the natural logarithm of *ZScore* and is defined as (ROA + Capitalization)/Standard deviation of ROA. In Column 1, the main independent variable of interest is *Retail CBDC Adoption*, which is an index that captures the level of retail CBDC adoption in each country. In Column 2, the main independent variable of interest is *Wholesale CBDC Adoption*, which is an index that captures the level of wholesale CBDC adoption in each country. Detailed definitions of all variables are in Table 2. Bank and year fixed effects are controlled in most of the models. Robust standard errors are in parentheses. *,**, and *** indicate significance levels at the 10 %, 5 %, and 1 %, respectively.

individuals and businesses) in everyday transactions. These digital currencies are backed by the issuing central bank, making them more secure than other forms of digital payments such as cryptocurrency. It would allow consumers to directly access central bank money for payments, store value, and other financial services without going through intermediaries like commercial banks. Wholesale CBDCs, on the other hand, are aimed at large-scale institutional investors and businesses. This type of CBDC is typically the settlement of interbank payment transactions with the reserves of credit institutions at the central bank (which does not directly serve the end users). Thus, it would be used primarily for interbank settlements and large-value transactions, allowing these entities to move funds between accounts quickly and securely without having to rely on third parties. Given that retail CBDC and wholesale CBDC are distinct in their features and usages, we postulate that the two types of CBDC will affect banks in different ways.

To test this, we augment the baseline model (1) and sequentially replace the independent variable, *CBDC Adoption*, with two variables capturing the level of retail CBDC and wholesale CBDC adoption, respectively. Specifically, *Retail CBDC Adoption* is an index that captures the level of retail CBDC adoption in each country. The same approach used to construct the *CBDC Adoption* index is used to construct *Retail CBDC Adoption* except that we now consider retail CBDC projects only. Specially, based on the information provided by each central bank or national authority responsible for researching and developing a CBDC in each country, we identify if the country in a given year is involved in any retail CBDC project or not. Then, in the second step, we constructed a time-varying retail CBDC adoption index (i.e. *Retail CBDC Adoption*) for the period from 2010 to 2021. Similar to the main *CBDC Adoption* index, the *Retail CBDC Adoption* index has its value ranked from 0 to 4, with a higher value indicating a higher level of development and adoption of retail CBDC. We similarly construct the *Wholesale CBDC Adoption* variable.

The results are presented in Table 11. The estimated coefficient on *Retail CBDC* is positive and statistically significant, indicating that retail CBDCs indeed promote system stability. Surprisingly, the estimated coefficient on *Wholesale CBDC* is negative and significant, indicating that wholesale CBDCs can hamper bank stability. The findings presented in Table 11 suggest that caution is needed when countries design and implement a wholesale CBDC.

6. Conclusion

The present study has analysed various aspects and implications of CBDC adoption. A comprehensive empirical exercise that draws on a global dataset allows us to conclude that the adoption of CBDCs is associated with a higher level of bank stability. That is, CBDC adoption contributes to financial stability by increasing the resilience of the banking system. Moreover, we conclude that large banks may benefit more than small banks from the adoption of CBDCs. This conclusion is in line with the view that large banks are more financially stable due to their more efficient use of risk tools and greater diversification. In this study, higher capitalization is also related to bank stability, possibly because a higher level of capitalization reflects a greater ability of banks to absorb risk. Similarly, traditional banking activities and deposit funding are associated with bank stability, consistent with the view that such activities are more stable over time. However, the analysis of loan loss reserve (as a reflection of ex-ante credit risk) suggests that it is negatively associated with financial stability. With regard to the macroeconomic control factors, we conclude that a higher level of domestic investment is beneficial for bank stability. Our main findings remain consistent when we account for bank, region and year fixed effects, alternative measures of CBDC adoption and bank stability, as well as alternative estimation approaches.

In light of the empirical findings on the role of CBDCs in risk dynamics and management in the banking sector, we conclude that the adoption of CBDCs may significantly reduce leverage risk and asset risk, and possibly also portfolio risk, though that result is not statically significant. Our findings suggest that the improvement of overall financial stability is not driven by portfolio risk, but by the reduction of leverage risk and asset risk. Important channels through which banks become more financially stable are by increasing lending (that is, benefiting from more stable traditional interest-bearing activities), improving loan quality, and lowering credit risk. We find the evidence that the overall increase in financial stability is driven by expanded lending, increased asset quality, and reduced ex-ante credit risk after the adoption of CBDC.

We also analyse *CBDC Adoption* for small, medium-sized and large banks separately. Our results lead us to conclude that CBDC adoption has positive effects for large banks and medium-sized banks, but not for small banks. These results support the notion that only banks of reasonable size become more financially stable following the adoption of a CBDC, while smaller banks may not be able to benefit in terms of financial stability.

Financialization and financial inclusion are important for any economy but especially so for emerging and developing economies. In this regard, CBDC adoption could be seen as a means to achieve financial stability and financial inclusion in emerging markets. In light of the empirical findings, we conclude that compared with developed economies, CBDC adoption is more beneficial for EMDEs.

Finally, on the basis of the comparative analysis between retail CBDCs versus wholesale CBDCs, we conclude that the retail CBDCs promote system stability, whereas wholesale CBDCs do not contribute to bank stability. Central banks and policymakers should give careful consideration to the implications of this for banking stability.

This paper has the limitation that since CBDCs are still in their early stages, it is difficult to accurately quantify their real impact. Therefore, any results discussed within this paper need to be interpreted with caution. Additionally, due to the nascent nature of CBDCs, further research is needed to better understand the implications of these new technologies and how they may affect existing financial systems. Lastly, there is also an aspect of stress testing where different central banks, financial institutions, regulators and authorities can make the CBDC adoption as the part of their stress testing frameworks.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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