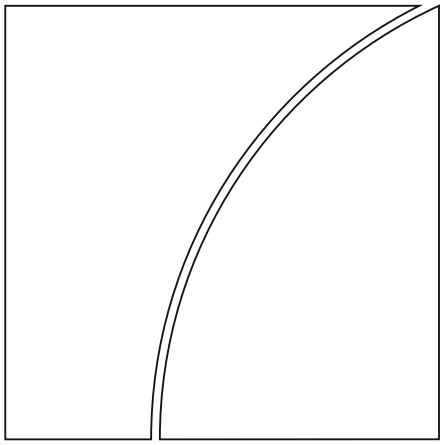


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Rise of the central bank digital currencies: drivers, approaches and technologies

by Raphael Auer, Giulio Cornelli and Jon Frost

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Rise of the central bank digital currencies: drivers, approaches and technologies*

Raphael Auer,♦ Giulio Cornelli♦ and Jon Frost♦†

Abstract

Central bank digital currencies (CBDCs) are receiving more attention than ever before. Yet the motivations for issuance vary across countries, as do the policy approaches and technical designs. We investigate the economic and institutional drivers of CBDC development and take stock of design efforts. We set out a comprehensive database of technical approaches and policy stances on issuance, relying on central bank speeches and technical reports. Most projects are found in digitised economies with a high capacity for innovation. Work on retail CBDCs is more advanced where the informal economy is larger. We next take stock of the technical design options. More and more central banks are considering retail CBDC architectures in which the CBDC is a direct cash-like claim on the central bank, but where the private sector handles all customer-facing activity. We conclude with an in-depth description of three distinct CBDC approaches by the central banks of China, Sweden and Canada.

Keywords: central bank digital currency, CBDC, central banking, digital currency, digital money, distributed ledger technology, blockchain.

JEL classifications: E58, G21.

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1. Introduction

Over the centuries, wave after wave of new payment technologies has emerged to meet societal demands. Coins, banknotes, cheques and credit cards were each innovations in their own day (Giannini (2011)). Today, there is growing discussion of a new payment technology: central bank digital currencies (CBDCs). As a digital liability of the central bank, wholesale CBDCs could become a new instrument for settlement between financial institutions, while retail (or general purpose) CBDCs would be a central bank liability accessible to all.[1]

Although the concept of a CBDC was proposed decades ago (ie Tobin (1987)), attitudes about whether central banks should issue them have changed noticeably over the past year. Initially, central banks focused on systemic implications that warranted caution (Barontini and Holden (2019)). But over time, the need to respond to the declining use of cash in some countries came to the fore, and a number of central banks have warmed to the idea of issuing a CBDC.[2] A tipping point was the announcement of Facebook's Libra and the ensuing public sector response. As of late 2019, central banks representing a fifth of the world's population reported that they were likely to issue CBDCs very soon (Boar et al (2020)). Similarly, the share of central banks (by number) that are likely to issue a retail CBDC over the medium term (in one to six years) doubled in 2019, to 20%. Meanwhile, a full 80% of surveyed central banks are engaging in research, experimentation or development of CBDCs.[3]

During the Covid-19 pandemic, social distancing measures, public concerns that cash may transmit the Covid-19 virus and new government-to-person payment schemes have further sped up the shift toward digital payments, and may give a further impetus to CBDC (see Auer et al (2020b)).

As a result, CBDCs have seized global attention and feature broadly in central bank communications and public search interest (Graph 1). Still, no major jurisdiction has decided to issue a retail CBDC, and many open questions remain. In the growing literature on CBDCs, discussions centre on several fundamental aspects. One is how central banks should create money and whether CBDCs are desirable in that context (Keister and Sanches (2019), Jackson and Pennacchi (2019), Kim and Kang (2019), Armelius et al (2020a)). Another area is the systemic implications of CBDCs and how to cope with them (Brunnermeier and Niepelt (2019), Fernández-Villaverde et al (2020), Kwon et al (2020), Carletti et al (2020)). There is also work on policy design frameworks (Davoodalhosseini and Rivadeneyra (2020), Agur et al (2019), Allen et al (2020)), their implications for cross-country payments (Milkau (2019)), implications for the international role of currencies (Ferrari et al (2020) and legal aspects of their issuance (Hess (2020), Duque (2020), Nabilou (2020), Belke and Beretta (2019)).

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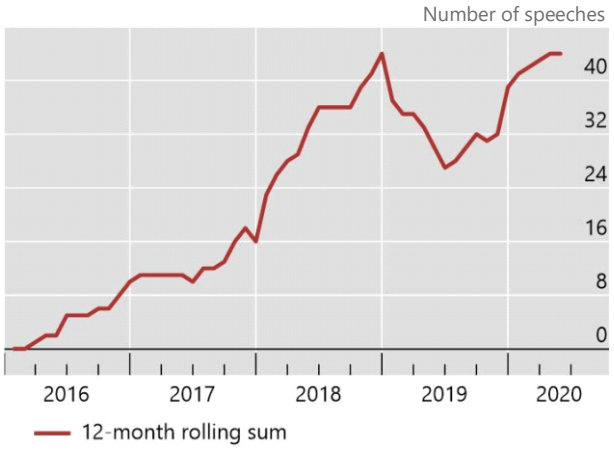
[1] "General purpose" and "retail" are used interchangeably to refer to CBDCs that individuals and non-financial firms could access. For an overview and relevant definitions, see Bech and Garratt (2017) and CPMI and Markets Committee (2018).

[2] Neither electronic money nor the discussion on the central bank's role in providing it directly to the people is new (ie Tobin (1987)). In the context of CBDCs, Broadbent (2016), Liikanen (2016), Mersch (2016), Wilkins (2016), Menon (2016), Skingsley (2016) and Nakaso (2016) were among high-level policymakers who argued early on that the idea should be taken seriously.

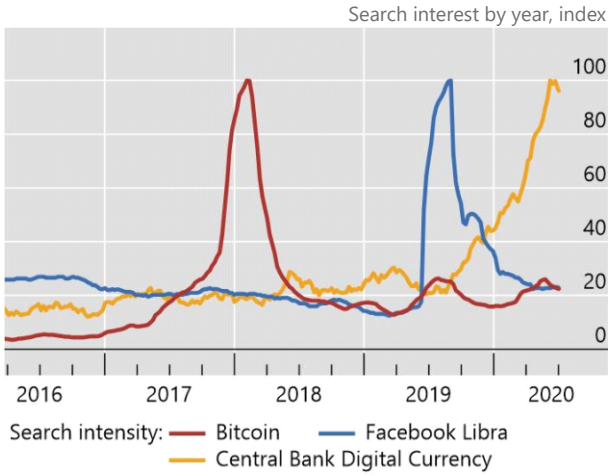
[3] Also in the private sector, the potential design and implications thereof are garnering substantial attention. See PwC (2019) and World Economic Forum (2020).

CBDCs: the next hype or the future of payments? Graph 1

Timing of speeches and reports on CBDC[1]



Google search interest over time[2]



[1] 12-month moving sum of the count of central bankers' speeches resulting from a case-insensitive search for any of the following words/phrases: CBDC; central bank digital currency; digital currency and digital money. [2] 12-week moving average of worldwide search interest. The data has been normalised to the 12-week moving average peak of each series. The search was run on search terms "Bitcoin" and "Facebook Libra" and topic "Central Bank Digital Currency". Data accessed on 16 July 2020.

Sources: Central bankers' speeches; central banks' websites; Google Trends; authors' calculations.

Finally, the technology of retail CBDCs and how they relate to private sector proposals is hotly contested (see Auer and Böhme (2020), Klein et al (2020), Clark and Mihailov (2019), Brunnermeier et al (2019) and Vives (2019)). Much less contentious is the issuance of wholesale CBDCs (see Bech et al (2020) and Pfister (2020)).

Amidst intense discussion in the research and policy spheres (BIS (2020)), and early development efforts, this study analyses the economic and institutional drivers of CBDC projects, thus shedding light on ultimate motivations. A next step is to understand the policy approaches and technical design of the various projects, and to look for commonalities and differences across countries.

The questions this paper aims to answer are: what are the economic and institutional drivers for issuing CBDCs? How do central banks approach the issues? What are the technical solutions sought? To answer these questions, we first develop a novel CBDC project index based on central bank research and development (R&D) projects. We then empirically investigate common factors in countries that are investigating and piloting CBDCs. We find that higher mobile phone usage (a measure of an economy's overall digitisation) and higher innovation capacity are positively associated with the likelihood that a country is currently researching or developing a CBDC. Retail CBDCs are more likely where there is a larger informal economy, and wholesale CBDCs are more advanced in economies that have higher financial development.

Next, we look at four attributes of CBDC technical designs, following the taxonomy of Auer and Böhme (2020). We show that a rising number of central banks are considering "Hybrid" or "Intermediated" architectures where the CBDC is a cash-like direct claim on the central bank, but the private sector manages customer-facing activity. Only a small number of jurisdictions is considering designs in which the central bank takes on an important operational role in the customer-facing side of

payments. None of the central bank reports favour a design with indirect claims on the central bank (referred to as an "Indirect" or "Synthetic" CBDC architecture).

Whereas many central banks are considering multiple technological options simultaneously, current proofs-of-concept tend to be based on distributed ledger technology (DLT) rather than a conventional technological infrastructure. Nevertheless, access frameworks tend to be based on account identification rather than allowing for token-based fully anonymous access. Most CBDC projects have a domestic focus. We examine how the features of these CBDCs fit with each other and the unique economic structures and preferences of their populations.

Finally, we show that the circumstances of each jurisdiction also matter for the policy approach taken to researching and developing a CBDC. Based on public reports and in-depth interviews with the experts in respective central banks, we describe three advanced approaches: the Chinese Digital Currency Electronic Payments (DC/EP), the Swedish e-krona and the Bank of Canada's CBDC contingency plan. While these projects are each tailored to their national context, there are lessons for other jurisdictions.

The rest of the paper is organised as follows. Section 2 describes current CBDC research and development efforts. Section 3 conducts empirical analysis on the drivers of CBDC projects. Section 4 discusses policy approaches and technical design. It gives a stocktake of four attributes of CBDC projects and relates these to economic indicators. Section 5 discusses the three selected projects. Section 6 concludes with policy implications and avenues for future research. The data collection process is described in Annex A. Annex B gives a tabular overview of CBDC projects. There is a separate online annex with further empirical results.

2. Taking stock of CBDC research and development efforts

Central banks around the world have been researching the concept and design of digital currencies for several years. As early as 2014, the Central Bank of Ecuador launched a project called "Dinero electrónico" (electronic money) to allow individuals to make mobile payments through a central bank-operated system (Valencia (2015)). Yet the system failed to attract a significant number of users, and was discontinued in 2016 (White (2018)).

Concurrently, with the growing popularity of Bitcoin and distributed ledger technology (DLT), a number of central banks have started internal projects to better understand DLT and its potential application to currencies. In the Netherlands, the Netherlands Bank ("De Nederlandsche Bank", DNB) did internal experiments starting in 2015 with a DLT-based coin called the Dukaton (DNB (2018)). This was named after the *dukaat*, a golden coin used at the time of Dutch independence from Spain in the 16th century. The Bank of England, Monetary Authority of Singapore, Bank of Canada and others ran similar internal experiments around this time. They generally concluded that DLT was not yet mature enough for use in major central bank payment systems (see Bank of England (2017)). In March 2016, the Deputy Governor of the Bank of England gave thoughts on the wide-reaching implications of CBDCs

(Broadbent (2016)) – the first of many subsequent policymaker speeches that have grappled with CBDCs and their implications for central banks and societies.[4]

From 2016 onward, a number of central banks launched research projects on digital currencies for specific purposes. The Bank of Canada launched Project Jasper (named after Jasper National Park in Alberta) in early 2016, and published a first report about the work the next year (Bank of Canada (2017)).[5] This project initially focused on DLT for the settlement of high-value interbank payments. The Monetary Authority of Singapore launched its own Project Ubin (named after the island Pulau Ubin) at the Singapore FinTech Festival in November 2016 (MAS (2016)). This, too, focused on interbank payments, and specifically on a tokenised form of the Singapore dollar on DLT.[6] The Hong Kong Monetary Authority (HKMA) launched Project LionRock (named after a mountain in Hong Kong) in January 2017. The European Central Bank (ECB) and the Bank of Japan launched the first known example of cooperation between two central banks on CBDCs in 2017 with Project Stella, focused on cross-border payments (ECB-BoJ (2017)).[7] Monetary authorities of Saudi Arabia and the United Arab Emirates, and of Hong Kong SAR and Thailand, also announced cross-border work on wholesale CBDCs (SAMA-UAECB (2019); BoT-HKMA (2020)).[8]

The first publicly announced work on retail CBDCs was conducted by the Swedish Riksbank (Sveriges Riksbank (2017)). In Sweden, cash use has been declining in recent years, and the Riksbank has initiated a societal discussion on access to a central bank payments instrument for the general public. Over time, this "e-krona" project has been further developed. In February 2020, the Riksbank announced it would conduct a pilot project with Accenture aimed at developing a proposal for a technical solution for an e-krona (Sveriges Riksbank (2020); see Section 4). While announced somewhat later, perhaps the most advanced CBDC project at present is that of the People's Bank of China (PBC). Known as the Digital Currency Electronic Payment (DC/EP), this CBDC is now being piloted in four cities in China (see Section 4). DC/EP will be a cash-like liability of the PBC available to the general public – and to foreign visitors of China – through account-based interfaces.

Meanwhile, the Bank of Canada has announced that is does not currently see a case for a retail CBDC, but that it is conducting work on retail CBDC as a contingency plan in case cash use suddenly declines or a private digital currency is widely adopted (see Section 4). The Eastern Caribbean Central Bank (ECCB) has launched a pilot called DXCD (ECCB (2019)), and the Central Bank of the Bahamas has launched a pilot called the Sand Dollar (CBB (2019)). Graph 2 gives a timeline of these and other projects.

---

[4] There were a number of earlier speeches on private digital currencies. For instance, in December 2013, the Governor of the Central Bank of Mauritius discussed digital currencies in a speech on the development of the local financial sector (Bheeninck (2013)). In 2015, the Deputy Governor of the Reserve Bank of India discussed private digital currencies in a speech (Gandhi (2015))

[5] In addition, the Bank launched a formal research agenda on electronic money and payments in 2013.

[6] The Bank of Canada, Bank of England and MAS subsequently worked in collaborative research with banks on challenges in cross-border payments and settlement and how various initiatives – including wholesale CBDC – could help. See Bank of Canada-MAS-Bank of England-HSBC (2018).

[7] Project Stella is so named because the flags of both the European Union (EU) and Japan depict stars. The EU musters 12 stars. The Japanese flag depicts the sun – the star in our solar system.

[8] The project by the Bank of Thailand and the HKMA is titled Inthanon-LionRock, after the tallest mountain in Thailand (Doi Inthanon) and the iconic Lion Rock in Hong Kong. SAMA-UAECB Project "Aber" refers to an Arabic word for a cross-road or moving from one place to another.

CBDC projects have proliferated since 2016

Graph 2

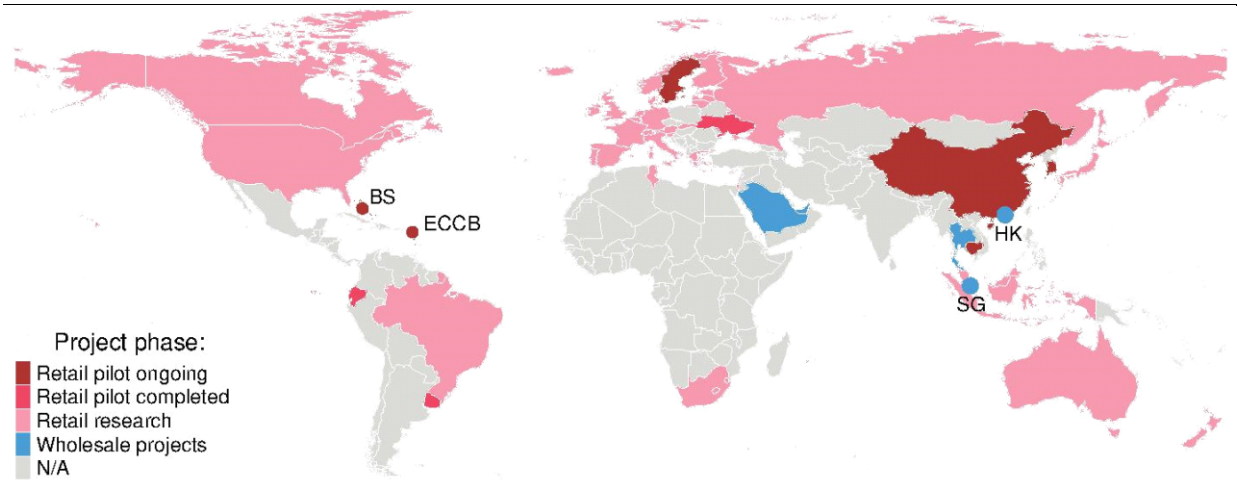


Sources: Central bankers' speeches; central banks' websites.

As of mid-July 2020, at least 36 central banks have published retail or wholesale CBDC work (Graph 3). At least three countries (Ecuador, Ukraine and Uruguay) have completed a retail CBDC pilot. Six retail CBDC pilots are ongoing: in the Bahamas, Cambodia (Bomakara (2019)), China, the Eastern Caribbean Currency Union,

CBDC projects status

Graph 3



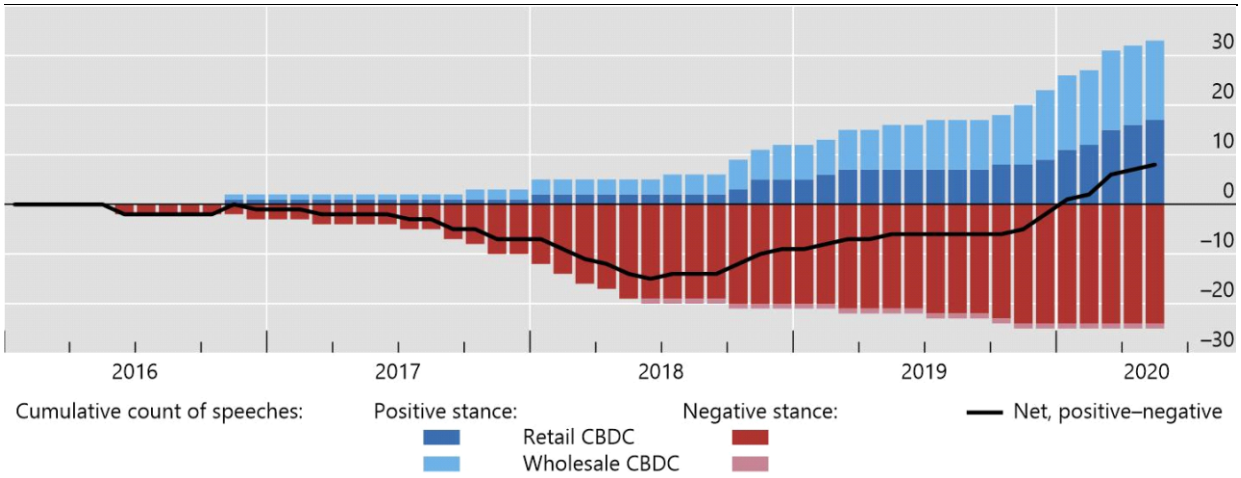
BS = The Bahamas; ECCB = Eastern Caribbean central bank; HK = Hong Kong SAR; SG = Singapore.

The use of this map does not constitute, and should not be construed as constituting, an expression of a position by the BIS regarding the legal status of, or sovereignty of any territory or its authorities, to the delimitation of international frontiers and boundaries and/or to the name and designation of any territory, city or area.

Source: central banks' websites.

Speeches on CBDCs have turned more positive since late 2018

Number of speeches Graph 4



Search on keywords "CBDC", "digital currency" and "digital money". The classification is based on the authors' judgment. The score takes a value of –1 if the speech stance was clearly negative or in case it was explicitly said that there was no specific plan at present to issue digital currencies. It takes a value of +1 if the speech stance was clearly positive or a project/pilot was launched or was in the pipeline. Other speeches (not displayed) have been classified as neutral.

Sources: centralbanking.com; Central bankers' speeches; central banks' websites; authors' calculations.

Korea (Bank of Korea (2020)) and Sweden).[9] Meanwhile, 18 central banks have published research on retail CBDCs (eg Harahap et al (2017), Burgos and Batavia (2018), Kiselev (2019) and Bank of Japan (2020)), and another 13 have announced research or development work on a wholesale CBDC.

In parallel, a growing number of central bank governors and board members have made public speeches about CBDCs. In 2017 and 2018, many of these had a negative or dismissive stance, particularly toward retail CBDCs. Since late 2018, the number of positive mentions of retail and wholesale CBDCs in speeches has risen, and in fact there have now been more speeches with a positive than a negative stance (Graph 4).

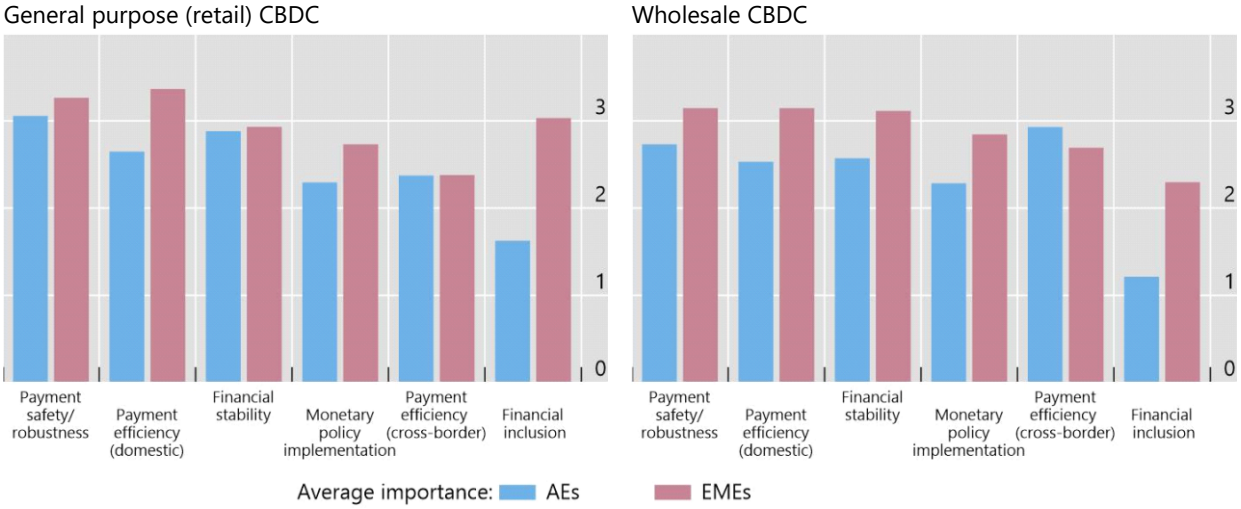
The motivations for such work differ across jurisdictions. Based on a survey of central banks in the BIS Committee on Payments and Market Infrastructures (CPMI) in late 2019, Boar et al (2020) show that in advanced economies (AEs), central banks are researching CBDCs to promote safety and robustness, or domestic payments efficiency (Graph 5). Financial stability concerns may also be an important driver of research and development work. Especially in emerging market economies (EMEs), financial inclusion is an important motivation.

[9] Additionally, the Marshall Islands, which currently use the US dollar as legal tender and do not have a monetary authority, have launched the SOV project, a digital currency proposed by private developers. We do not include this project in our database. See IMF (2018) for a critical discussion.

Motivations for issuing a CBDC

Average importance

Graph 5



1 = not so important; 2 = somewhat important; 3 = important; and 4 = very important.

Sources: CPMI survey of central banks; Boar et al (2020).

Recently, the Covid-19 pandemic may have accelerated work on CBDCs in some jurisdictions. For instance, in the United States, early versions of Congress bills on fiscal stimulus included references to a "digital dollar" as a means of quickly executing government-to-person payments, as an alternative to credit transfers and slow and costly cheques (Brett (2020)). In parallel, the Federal Reserve has continued its ongoing research on retail CBDCs (Brainard (2020a, b)). In the Netherlands, the central bank has emphasised that the pandemic underscores the need for a backup to private money (DNB (2020)). In China, pilot testing for the new CBDC is coinciding with a phasing out of pandemic-related mobility restrictions. In Sweden, testing of the e-krona project continues even amidst central bank crisis management measures.

It should be noted that retail payment behaviours show great inertia. For example, Brown et al (2020) find that an exogenous introduction of more convenient payment methods led only to a moderate average reduction in the cash share of payments. Arifovic et al (2017) show with experimental evidence how fees influence the behaviour of buyers and sellers, and ultimately the take-up of a new payment method. However, when behaviours change, they often do so quite persistently. In the same manner, changed payment behaviours caused by the Covid-19 crisis, such as a greater use of digital payments, could have far-reaching effects in the future.

3. The cross-country drivers of CBDC development

Several global developments – including the digitalisation of commerce, the rise of private digital currencies and concerns that cash may transmit the Covid-19 virus – have recently driven increased interest in CBDCs. Yet the economic and institutional motivations for issuance vary according to the country.

In this section, we seek to explain the cross-country dimension of CBDC research and development based on economic and institutional drivers. Specifically, we want to find commonalities in *why* central banks choose to embark on – or step up – CBDC efforts in some countries more than in others, using cross section regressions. This will also help us to understand *how* they design CBDC projects.

We thus build a CBDC project index, and then seek to explain its development across countries and over time.

A novel CBDC database

We start by generating a novel global index measuring the central bank's progress toward the development of a retail or wholesale CBDC: the **CBDC project index (CBDCPI)**. This index captures publicly announced work by the central bank on CBDC projects. This is equal to 0 when there is no announced project, 1 in the case of public research studies, 2 in the case of an ongoing or completed pilot and (a so-far hypothetical) 3 for a live CBDC. We construct one sub-index each for retail and wholesale CBDC projects, and an overall index equal to the maximum of the two sub-indices. The information was collected through desk research and with the help of contacts at several individual central banks.[10]

Separately, we have calculated two different indicators:

- A **central bank speech score**, which reflects discussion of CBDCs in speeches by central bank management, including the stance (whether positive or negative). This is set to –1 if the authors judge that the speech stance was clearly negative or in the case it was explicitly said that there was no specific plan at present to issue a CBDC. It takes a value of 0 in the case of a neutral stance. Finally, it takes a value of +1 if the speech stance was clearly positive or if a CBDC project/pilot was launched or was in the pipeline. For each country, the aggregate score is a simple average of the individual speech stances.

- A **search interest index** corresponding to Google Trends or (for China) Baidu searches in each country on "CBDC" and related terms by the general public.[11] This score is equal to the simple average of the search intensity of the individual keywords for the period January 2013–April 2020. The score reflects both interest by citizens in the idea of a CBDC, and how widely known any central bank plans to introduce a CBDC are with the public.

For each of the indicators described above, we replace country-level missing observations with zeros. This choice is consistent with the absence of a project (research or pilot), a neutral stance towards the development of a CBDC (speech score) or a lack of public interest (as captured by the search intensity score).

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[10] The list of projects is broadly consistent with other stocktakes, such as Kiff et al (2020) and Atlantic Council (2020). We only take account of official central bank communications, not press articles.

[11] For China, we use the Baidu index for keywords "Central Bank Digital Currency" and "DC/EP". Baidu index data directly measure the daily number of searches. To compare this with Google Trends data, we re-index the data to a peak of 100. Next, we reduce the frequency, taking the monthly maximum. Finally, we calculate a simple average of the two series for the period 2013–current. See Annex A for a detailed explanation.

These indicators – made available with this paper – can help to gauge the project work on CBDCs in specific countries and to compare it with communications by central banks and public interest. The CBDC project index and both the speech and search interest scores display substantial variance in the cross section. Naturally, the three variables are correlated with one another, as central bank board members often use speeches to broadcast project work, and public search interest may be higher where central banks have communicated that they are working on a project (see pairwise correlations in Table 1).

Pairwise correlations

Table 1

	CBDC project index[1] (overall)	Central bank speech score[2]	Search interest index (Google/Baidu)[3]
CBDC project index[1] (overall)	1.00		
Central bank speech score[2]	0.52***	1.00	
Search interest index (Google/Baidu)[3]	0.40***	0.20***	1.00

*** denotes significance at the 1% level.

[1] The project stance is equal to 0 when there is no known work on retail or wholesale CBDC, 1 in the case of research output, and 2 in the case of an active or completed retail or wholesale CBDC pilot. [2] Search on keywords "CBDC", "digital currency" and "digital money". The classification is based on the authors' judgment. The score takes a value of –1 if the speech stance was clearly negative or in case it was explicitly said that there was no specific plan at present to issue digital currencies. It takes a value of +1 if the speech stance was clearly positive or a project/pilot was launched or was in the pipeline. Other speeches (not displayed) have been classified as neutral. Normalised and winsorised at the 5% level. [3] Data have been normalised.

Sources: Baidu; central banks' websites; BIS Central Bankers' Speeches; Google Trends; authors' calculations.

There are necessarily caveats to these measures. For instance, many central banks have not publicly released reports on their ongoing CBDC projects. Some central banks (eg PBC) have quite advanced projects, but have given relatively few speeches on their plans. In some jurisdictions, Google (or Baidu) is not widely used for internet searches. Still, the index can provide a comparable yardstick to assess changes across countries and over time. Moreover, this can provide a useful complement to the anonymised responses of central banks through official surveys. In the next section, we try to explain the cross-country heterogeneity in the CBDC project index.

Examining the cross-country drivers of CBDC projects

In this section we investigate the drivers of the CBDC project index. To complement central bank surveys and official motivations, we look at "revealed policy preferences", ie the economic and institutional factors that are associated with central banks' actual work on overall, retail or wholesale CBDCs. Our cross section estimations use an ordered probit approach (McKelvey and Zavoina (1975)), and take the form of:

$$Prob(CBDCPI_i = 0,1,2,3|x_i) = F(\alpha + \beta x_i + \varepsilon_i)$$

where $Prob(CBDCPI_i = 0,1,2,3|x_i)$ is the probability that the CBDC project index (overall, or for retail or wholesale projects) in jurisdiction i equals 0 (no project), 1 (research), 2 (pilot) or 3 (live CBDC), F() is the functional form of ordered probit, X_i is one or more variables from a vector of potential drivers, α and β are estimated coefficients and ε_i is an error term.

Some of the potential drivers of CBDC development can be related to factors affecting a country's technological capability to develop and deploy a CBDC. Focusing on indicators from reliable sources that are available for a wide cross section of countries, we include in our analysis the following indicators:

- **Digital infrastructure:** jurisdictions with greater **mobile phone use** (mobile cellular subscriptions per 100 people) or **internet use** (fixed line broadband subscriptions per 100 people) may have a more developed infrastructure for the central bank to develop CBDCs. Data on both come from the World Bank.
- **Innovation capacity:** jurisdictions with a higher **innovation score** overall, and hence the ingenuity and R&D potential to support central banks in designing a new CBDC ecosystem, may be more likely to see CBDCs. Data come from the World Intellectual Property Organization (WIPO) Global Innovation Index, which aggregates measures in the political environment, education, infrastructure and business sophistication (WIPO (2018)). To look at the innovation capacity of the central bank, itself, we have a dummy for countries that have in place or plan to institute a retail fast payment system (FPS). Data for this come from Bech and Boar (2019).
- **Institutional quality:** jurisdictions with higher **government effectiveness** may be more likely to launch CBDC projects. Data come from the World Bank. Conversely, central banks in jurisdictions with a large **informal ("shadow") economy** may have greater interest in creating a data trail for transactions, and thus promoting use of a digital currency. Estimates of the size of the informal economy come from Medina and Schneider (2019).

On the other side, countries may differ in their perceived demand for a CBDC. To proxy these factors, we include the following indicators:

- **Development and financial inclusion:** countries that are more developed, as measured by **GDP per capita**, may see a higher demand for new digital payment methods. At the same time, all else equal, jurisdictions with lower **access to transaction accounts** may see a greater need for retail CBDCs as a financial inclusion policy. Data come from the World Bank Findex.[12] Meanwhile, jurisdictions with higher **financial development** may have greater demands on innovative solutions for wholesale settlement; data for this are available from Svirydzenka (2016).
- **Public interest in CBDCs:** where the public has more **internet searches** for CBDCs and related topics, this may signal either that they are more aware of the topic of CBDCs in general, or the plans of their own domestic central bank in this area. Either way, a positive association can be expected. Data are from Google and Baidu, as discussed above.
- **Cross-border transactions:** while most CBDCs serve a domestic purpose, one could expect that especially internationally oriented CBDCs (eg projects for cross-border interbank settlement or migrant remittances) may be more likely in more internationally integrated economies. **Trade openness** (the sum of imports and exports over GDP) can proxy for cross-border demand for new payment options for goods and services. **Remittance flows** (inflows

[12] We have also looked at various measures of cash use, such as small-denomination banknotes to GDP. These are available from the CPMI Red Book statistics, but unfortunately for only 18 jurisdictions.

and outflows divided by GDP) gauge the economic importance of migrants' remittances. Again, both series come from the World Bank.

Descriptive statistics[1] Table 2

	Observations	Mean	Standard deviation	Min	Max
Dependent variables					
Overall CBDC project index	175	0.31	0.66	0	2
Retail CBDC project index	175	0.22	0.53	0	2
Wholesale CBDC project index	175	0.13	0.48	0	2
Independent variables					
Mobile cellular subscriptions (per 100 people)	169	109.24	39.54	12.60	320.55
Broadband subscriptions (fixed line, per 100 people)	167	13.60	13.38	0	47.16
Innovation output score (WIPO)	118	29.67	12.69	7.90	67.13
Fast payment system dummy	175	0.37	0.48	0	1
Government effectiveness	175	0.08	0.99	-2.24	2.19
Informal economy (% of GDP)	122	26.08	11.62	5.43	55.78
GDP per capita (USD)	168	16,652	21,423	301	110,344
Account ownership (% age 15+)	135	60.39	27.96	6.45	99.96
Financial development index[2]	158	0.36	0.22	0.06	0.93
Search interest index (Google/Baidu)[3]	175	0.11	1.13	–0.34	8.18
Remittances[4] to GDP	110	5.89	7.86	0.19	41.18
Trade openness[5]	134	80.05	48.87	0	345.69
Central bankers' speech stance index[7]	175	0.02	0.47	–0.13	1.68

[1] For all the independent variables, average over the period 2013–19, subject to data availability. [2] Svirydzenka (2016). [3] Data have been normalised. [4] Sum of inflows and outflows. [5] Sum of imports and exports divided by the country GDP. Data for 2018. [6] Data for 2014; for EA, latest observation available (2010). [7] Normalised and winsorised at the 5% level.

Sources: Bech at al (2020); Medina and Schneider (2019); Svirydzenka (2016); WIPO (2018); IMF, *World Economic Outlook*; World Bank, *Remittance Prices Worldwide*, remittanceprices.worldbank.org; World Bank; Baidu; central banks' websites; BIS Central Bankers' Speeches; Datastream; Google Trends; authors' calculations.

Table 2 gives descriptive statistics for our sample. For our CBDCPI, we have 175 observations. This includes a number of jurisdictions that are part of a currency union. In these cases, we count jurisdictions only if they have a central bank that could in theory develop a CBDC; currency unions without national central banks are considered one observation, with all independent variables calculated as weighted averages according to 2018 GDP.[13] Mobile cellular subscriptions range from 13 per

[13] For this reason, the 19 euro area members are included individually, plus an additional observation for the ECB, given the ECB's research work (project score of 1). For individual euro area members, values of the CBDC project index are 1 or 0 depending on work by national central banks. On the other hand, the eight members of the Eastern Caribbean Currency Union (ECCU) are aggregated to one observation, with a project score of 2 given the ECCB pilot. Empirical results are robust to dropping the individual euro area member countries from the sample. See Annex A for data construction.

100 people (North Korea) to 321 (Macao), and GDP per capita ranges from USD 281 (Burundi) to USD 110,343 (Luxembourg). For some key variables (eg the innovation output score, estimates of the informal economy, account ownership and remittances) coverage is lower, but generally still well above 100 jurisdictions.

Table 3 displays our univariate regression results. We can confirm that the CBDC project index is strongly associated with higher mobile and internet use, a higher innovation capacity, an existing or planned FPS and greater government effectiveness. It is also higher in jurisdictions with higher search interest for CBDCs. Somewhat against our expectations, there is a negative association with the informal economy in these univariate estimations; as we will see below using a multivariate approach, this relates to the correlation of this variable with mobile use and other positively associated covariates. Further when it comes to those factors potentially affecting the demand for CBDC, we find CBDC projects to be more advanced where there is higher GDP per capita, financial development and search interest. Higher account ownership is associated with more advanced CBDC project work, while remittances are negatively correlated. As a simple robustness check, we have performed the same analysis with ordinary least squares (OLS). Results (available in an online annex) are broadly consistent. Similarly, the univariate results are very similar for the retail and wholesale indices separately.

Of course, these simple regression coefficients need to be interpreted with great care as many of the regressors are collinear (see online annex). More advanced economies tend to be more digitised, more innovative and to feature more effective goverments and smaller informal economies. Moreover, isolating individual drivers is complicated by the fact that sample size for some indicators is more limited, thus not allowing us to include all possible regressors at the same time.

To better control for multiple country characteristics, Table 4 displays multivariate ordered probit regression results for the overal CBDC project index, and for retail and wholesale CBDCs. Here, we confirm that overall projects are more likely where there is greater use of mobile phones and greater innovation capacity. For example, a one standard deviation increase in mobile phone subscriptions is associated with a 55–63% higher probability of moving from no work to research, or from research to a pilot (assuming mean levels of all independent variables).[14] A one standard deviation increase in the innovation output score is associated with a 55% higher probability. In this case, controlling for mobile use and other positively associated covariates, we also find a significant association with the size of the informal economy and financial development for the overall project index. We do not find a significant link with trade openess.

[14] There are necessarily caveats to this simple calculation given the non-linear nature of the ordered probit and correlation between the independent variables. For a discussion of interpretation issues in logits, probits and other non-linear probability models, see Breen et al (2018).

Univariate ordered probit regressions on overall CBDC project index[1]

Table 3

Digital infrastructure												
Mobile cellular subscriptions	0.010***											
(per 100 people)	(0.004)											
Broadband subscriptions		0.042***										
(fixed line, per 100 people)		(0.008)										
Innovation capacity												
Innovation output score			0.047***									
(WIPO)			(0.009)									
Fast payment system (FPS) dummy				0.882***								
				(0.221)								
Institutional characteristics												
Government effectiveness					0.674***							
					(0.118)							
Informal economy						–0.03***						
(% of GDP)						(0.013)						
Development and financial inclusion												
Ln(GDP per capita)							0.439***					
							(0.092)					
Account ownership								0.023***				
(% age 15+)								(0.005)				
Financial development index[2]									3.414***			
									(0.552)			
Public interest in CBDCs												
Search interest index (Google/Baidu)[3]										0.432***		
										(0.098)		
Cross-border transactions												
Remittances[4] to GDP											–0.157**	
											(0.068)	
Trade openness[5]												0.001
												(0.003)
Number of observations	169	167	118	175	175	122	168	135	158	175	110	134
Pseudo R^2	0.057	0.126	0.129	0.074	0.145	0.058	0.119	0.131	0.215	0.105	0.113	0.001

Robust standard errors in parentheses; ***/**/* denotes results that are significant at the 1/5/10% level.

[1] For all the independent variables, average over the period 2013–19, subject to data availability. [2] Svirydzenka (2016). [3] Data have been normalised. [4] Sum of inflows and outflows. [5] Sum of imports and exports divided by the country GDP. Data for 2018.

Sources: Bech et al (2020); WIPO (2018); Medina and Schneider (2019); Svirydzenka (2016); IMF, *World Economic Outlook*; World Bank, *Remittance Prices Worldwide*, remittanceprices.worldbank.org; World Bank; Baidu; central banks' websites; Datastream; Google Trends; authors' calculations.

Multivariate ordered probit regressions on CBDC project indices[1] Table 4

	Overall CBDC project index		Retail CBDC project index		Wholesale CBDC project index	
Mobile cellular subscriptions	0.013**	0.015***		0.011**		0.022**
(per 100 people)	(0.005)	(0.006)		(0.005)		(0.010)
Innovation output score	0.045***		0.067***	0.082***		
(WIPO)	(0.010)		(0.017)	(0.019)		
Informal economy		0.027*	0.033*	0.042***		-0.009
(% of GDP)		(0.015)	(0.018)	(0.016)		(0.026)
Financial development		3.909***			3.303***	4.287***
Index[2]		(0.867)			(0.775)	(1.299)
Trade openness[3]		-0.003		-0.016**	0.004*	-0.001
		(0.004)		(0.007)	(0.003)	(0.004)
Number of observations	118	105	110	100	132	105
Pseudo R^2	0.167	0.241	0.144	0.244	0.263	0.352

Robust standard errors in parentheses; ***/**/* denotes results that are significant at the 1/5/10% level. Constants are not reported.

[1] For all the independent variables, average over the period 2013–2019, subject to data availability. [2] Svirydzenka (2016). [3] Sum of imports and exports divided by the country GDP. Data for 2018.

Sources: Medina and Schneider (2019); WIPO (2018); IMF, *World Economic Outlook*; World Bank; central banks' websites; Datastream; authors' calculations.

Retail CBDCs, also appear to be more advanced in jurisdictions with high innovation capacity and where the informal economy is larger, all else equal. A one standard deviation increase in the size of the informal economy is associated with a 38–49% probability of moving one unit up in the CBDC project index, all else equal. This result, obtained only when controlling for other factors, could relate to a desire by authorities to have a data trail for transactions, as discussed above.

Wholesale CBDCs are positively correlated with financial development, which could reflect the focus of such projects on increasing the efficiency of wholesale settlement.[15] In the more parsimonious specification, there is a link with trade openness. As many wholesale projects focus on the cross-border dimension, this link is also intuitive.

These results, as well, are robust to using OLS (in online annex).

4. Policy approaches and technical design

We have thus far established that CBDCs are more likely to be under research and development in jurisdictions with high mobile use, innovation capacity and search interest for CBDCs, with some differences across retail and wholesale CBDCs. We have also noted that CBDC projects differ starkly across countries, both in their economic and institutional motivations, policy approach and their technical design.

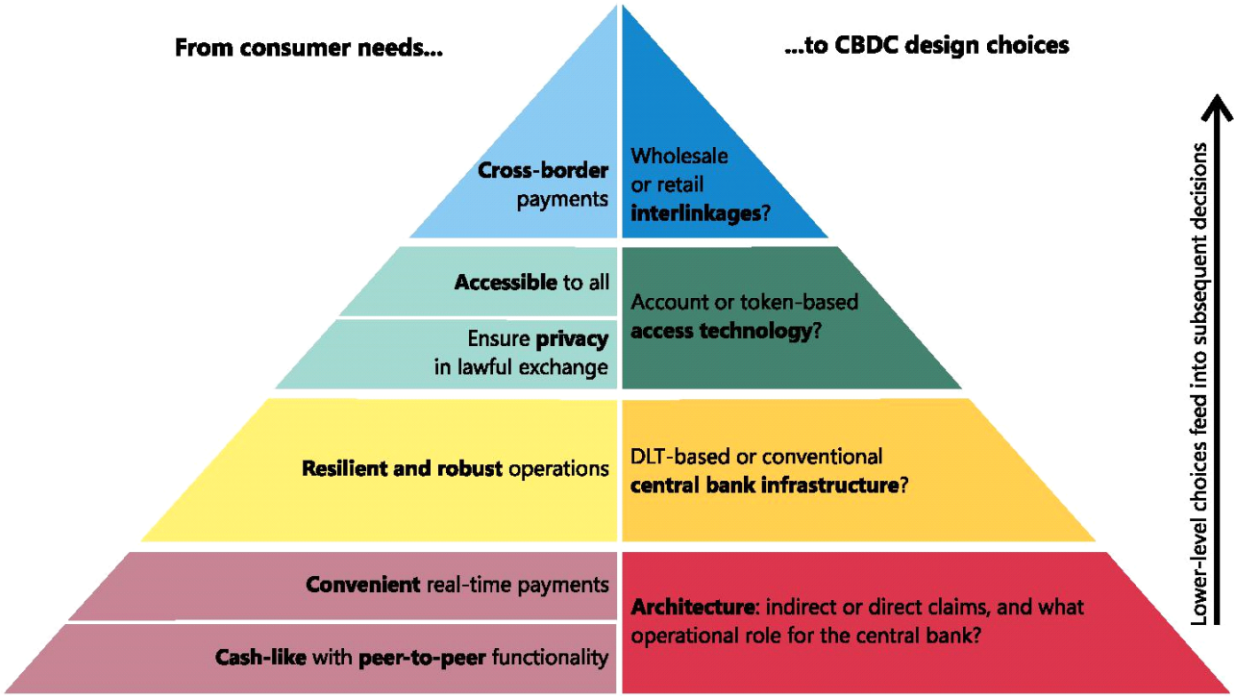
[15] The innovation output score is not included, given high correlation with financial development (81%).

In what follows, we focus only on the 30 retail CBDC projects in our sample (see Annex C). We explore four key technological attributes of retail CBDC projects, and the economic and institutional factors correlated with their use.

A stocktaking framework: the CBDC Pyramid

Approaches to CBDC design are heterogeneous across countries, requiring us to distil the main design choices and the dimensions along which national approaches differ. One way to classify design approaches is the "CBDC Pyramid" (see Auer and Böhme (2020) and Graph 6). This approach starts from the consumer needs that a retail CBDC could address, identifies associated technical design trade-offs, and then derives the design choices. The scheme of design choices forms a hierarchy in which the lower, initial layers represent design decisions that feed into subsequent, higher-level decisions. To reflect this hierarchy, the choices are displayed as a pyramid.

The CBDC pyramid — Graph 6



The CBDC pyramid maps consumer needs onto the associated design choices for the central bank. The left-hand side of the CBDC pyramid sets out the consumer needs and associated features that would make a CBDC useful. The pyramid's right-hand side lays out the associated trade-off – forming a hierarchy in which the lower layers represent design choices that feed into subsequent, higher-level decisions.

Source: Auer and Böhme (2020).

The first and foundational design choice is the **architecture**, ie which operational role the central bank and private intermediaries take on in a CBDC. Intermediaries can run into technical difficulties or solvency issues. A CBDC should be safe from such outages. Yet payment intermediaries offer valuable services to consumers, which are needed to ensure the same level of convenience, innovation and efficiency as in today's payments. The architecture needs to balance these two considerations.

We augment Auer and Böhme (2020) by classifying various proposals for CBDC design into **four distinct CBDC architectures**. These differ in the structure of legal claims and the record kept by the central bank. They are:

- ***Direct CBDC*** – a payment system operated by the central bank, which offers retail services. A CBDC is a direct claim on the central bank. The central bank maintains the ledger of all transactions and executes retail payments.
- ***Hybrid CBDC*** – an intermediate solution that runs on two engines. Intermediaries handle retail payments, but the CBDC is a direct claim on the central bank, which also keeps a central ledger of all transactions and operates a backup technical infrastructure allowing it to restart the payment system if intermediaries fail.
- ***Intermediated CBDC*** – an architecture similar to Hybrid CBDC, but in which the central bank maintains only a wholesale ledger, rather than a central ledger of all retail transactions. Again, the CBDC is a claim on the central bank and private intermediaries execute payments. For the purposes of this paper, this will be considered alongside the Hybrid model in our stocktake.

In addition to these three generally recognised general purpose CBDC architectures, another approach is the indirect provision of retail CBDC via financial intermediaries. We note that, as this does not allow the consumer to directly access central bank money, not all central banks recognise this architecture as a general purpose CBDC.[16]

- ***Indirect or Synthetic CBDC*** – a payment system operated by intermediaries that resemble narrow payment banks. Consumers have claims on these intermediaries, which operate all retail payments. These intermediaries need to fully back all liabilities to retail clients with claims on the central bank.[17]

The second technical design choice regards the **infrastructure**. A CBDC must be secure from outages at the central bank. The infrastructure can be based on a conventional centralised database or instead on DLT. These technologies differ in their efficiency and degree of protection from single points of failure. DLT often aims to replace trust in intermediaries with trust in an underlying technology. Calle and Eidan (2020) describe some of these proofs-of-concept in detail. Also noteworthy is that all central banks experimenting with DLT use permissioned variants, where operators can decide who is admitted to the network. No central bank report examined in this study has ventured to rely on permissionless DLT, as used for Bitcoin and many other private cryptocurrencies.[18]

The third choice concerns how consumers can **access** the CBDC. Account-based CBDCs are tied to an identity scheme, which can serve as the basis for well-functioning payments with good law enforcement. Yet access is likely to be difficult for one core target group: the unbanked and individuals who rely on cash. There may be challenges to match the qualities of cash as an inclusive, crisis-proof and anonymous means of payment (Pichler et al (2019)). An alternative is to base access on so-called

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[16] For example, Sveriges Riksbank (2020), Bank of England (2020), and for the case of Canada, Dinesh et al (2020) only consider architectures featuring direct claims on the central bank.

[17] See Adrian and Griffoli-Mancini (2019) and Kumhof and Noone (2019).

[18] See Auer (2019) for a discussion of the inefficient economics of permissionless models and Ali and Narula (2020) for a specific analysis of permissioned and permissionless DLT in the context of CBDCs.

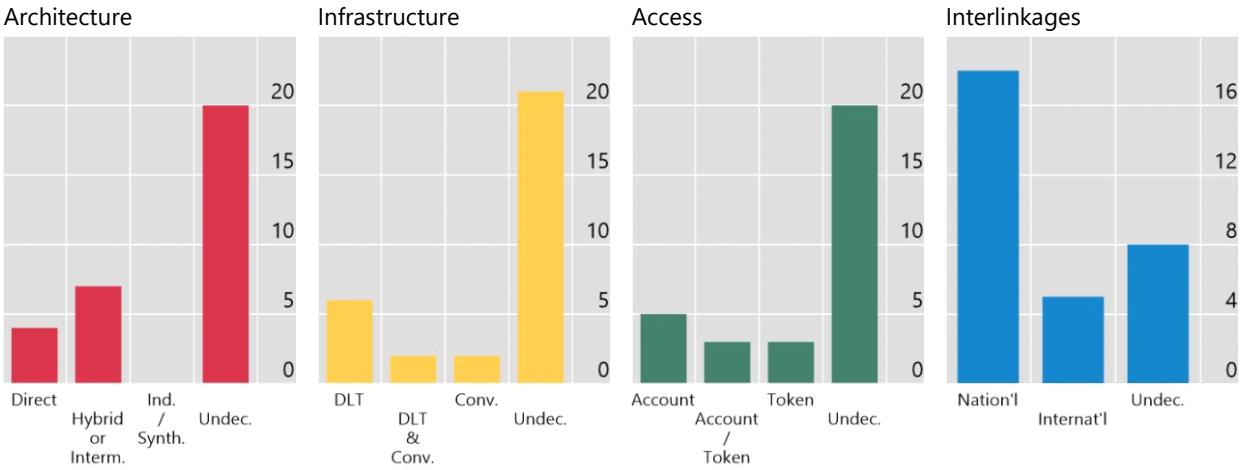
digital tokens.[19] This allows for value-based payment options, for example pre-paid CBDC banknotes that can be exchanged both physically and digitally. Yet this also brings new risks of illicit activity and counterfeiting.

Closely tied to the domestic access framework is the fourth design choice, the use of CBDC for **cross-border payments**, which relates to the retail and wholesale interlinkages in a CBDC's design and its accessibility for residents vs non-residents. Token-based domestic access would naturally be open to anyone, including non-residents. But central banks may allow for use by non-residents.

Graph 7 classifies the attributes of ongoing retail CBDC projects. Among the retail CBDC projects in our sample, we find a wide variety of approaches to architecture, infrastructure, access and cross-border (retail or wholesale) interlinkages. On architecture, we find four central banks considering a Direct model (often to enhance financial inclusion). Seven are considering the Hybrid or Intermediated options (in some cases alongside a Direct option), and a larger group has not yet specified the architecture. No report examined in this study indicates that a central bank is pursuing the Indirect/Synthetic architecture.

Attributes of retail CBDC projects

Number of retail CBDC projects investigating each design option — Graph 7



Interm. = Intermediated; Ind. = Indirect; Synth. = Synthetic; Undec. = undecided/unspecified or multiple options under consideration; DLT = distributed ledger technology; Conv. = Conventional; Nation'l = national use; Internat'l = international use.

Sources: central banks' websites; authors' calculations.

Regarding infrastructure, we find seven central banks running their prototypes on DLT, three with conventional technology and one considering both (Shah et al (2020)). Yet these infrastructure choices are often for first proofs-of-concept or pilots. Only time will tell if the same choices are made for large-scale designs. Among access

[19] Importantly, this definition of token versus accounts must not be confused with the one used in the field of computer science. Rather, it follows Kahn and Roberds (2009). As put by Kahn (2016), the distinction between accounts and tokens are the identification requirements: "In a token-based system, the thing that must be identified for the payee to be satisfied with the validity of the payment is the "thing" being transferred – "is this thing counterfeit or legitimate?" In an account-based system, however, the identification is of the customer – "Is this person who she says she is? Does she really have an account with us?"

methods, account-based access appears to be the most common to date, with six central banks clearly leaning toward account-based and a further two looking at both account and token-based access. Finally, while most of the projects in our sample are focused on domestic use, several of them – by the ECB, the central banks of France, Spain and the Netherlands, and the ECCB – are by construction focused on cross-border use among the members of a multi-country currency area.

The drivers of technological designs

Central banks choose these different attributes of CBDCs in line with the unique needs of their jurisdictions, but there may nonetheless be common features across countries.[20] In this light, we have also performed simple probit regressions for three of the four attributes (Table 5; moreover, a figure in the online annex represents this graphically). Indicators were chosen based on the statistical significance of differences between the projects; the top three are presented in each case. Because of the lack of variation in our sample regarding cross-border interlinkages, these differences are not presented.

For the architecture, one may expect that the Direct or Hybrid and Intermediated options would be more likely in economies that are less developed or have less financial inclusion. In fact, we find the opposite: likely due to the influence of the Nordic countries, Canada and China, we find that it is *higher*-income jurisdictions, with greater account access and government effectiveness, that are more likely to choose a Direct or Hybrid and Intermediated architecture – at least in research work to date. Less developed countries have generally not specified their chosen architecture.

Regarding infrastructure, we expect that DLT – originally designed to substitute for trusted intermediaries – is more attractive in jurisdictions in which authorities are perceived to be less effective. This difference is not statistically significant. Some central banks do note explicitly that DLT presents no fundamental advantages when using a centralised issuance system (NBU (2019)). On the other hand, countries researching or piloting DLT are more dependent on inward remittance flows than countries researching or piloting conventional architectures.

Regarding account-based vs token-based access, we find that countries looking at tokens have higher public search interest, but also lower remittance inflows. These differences are only significant at the 10% level.

[20] We note that central banks often consider multiple design options, to retain full flexibility when it comes to achieving the wide range of objectives such as privacy, monetary policy, inclusion, or financial stability.

Univariate probit on retail CBDC project features[1] Table 5

	Architecture 1: Direct and Hybrid or Intermediated 0: Indirect / unspecified			**Infrastructure** 1: DLT infrastructure 0: Conventional / unspecified			**Access** 1: Token-based 0: Account-based / unspecified		
Government effectiveness	0.599**								
	(0.299)								
Ln(GDP per capita)		0.600**							
		(0.249)							
Account ownership (% age 15+)			0.033**						
			(0.015)						
Remittance inflows to GDP				0.205**					
				(0.096)					
Informal economy					0.02				
(% of GDP)					(0.023)				
Trade openness[2]						0.006			
						(0.007)			
Search interest index							0.157		
(Google/Baidu)[3]							(0.131)		
Remittance outflows to GDP								-1.873**	
								(0.828)	
Innovation output score									-0.008
(WIPO)									(0.022)
Number of observations	31	31	27	28	27	31	31	26	28
Pseudo R^2	0.103	0.150	0.148	0.118	0.027	0.0191	0.046	0.186	0.005

Robust standard errors in parentheses; ** denotes results that are significant at the 5% level. Constants are not reported.

[1] For all the independent variables, average over the period 2013–19, subject to data availability. [2] Sum of imports and exports divided by the country GDP. Data for 2018. [3] Data have been normalised.

Sources: WIPO (2018); Medina and Schneider (2019); IMF, *World Economic Outlook*; World Bank, *Remittance Prices Worldwide*, remittanceprices.worldbank.org; World Bank; Baidu; central banks' websites; Datastream; Google Trends; authors' calculations.

5. Approaches for CBDC design: three examples

In the above analysis, we have thus far conducted a study of the drivers of CBDC interest and how the economic and institutional characteristics of each jurisdiction shape technological CBDC design choices. The circumstances of each jurisdiction also matter for the policy approach taken to researching and developing a CBDC. We believe that there can be great value in central banks learning from one another's approaches – an activity that is promoted by international policy discussions (BIS (2020)) and the publications of central banks. To complement this work, we describe three unique CBDC approaches, one each in Asia, North America and Europe.

To make the discussion of design choices more concrete, we showcase three prominent retail CBDC projects, namely the People's Bank of China's Digital Currency

Electronic Payment (DC/EP) project; the Swedish Riksbank's e-krona; and the work by the Bank of Canada on a CBDC as a contingency plan.

PBC: the DC/EP project (pilot stage)

Among all current CBDC projects, the one by the People's Bank of China (PBC) is at the most advanced stage. CBDC development efforts in China go back to at least 2014. In late 2019, the PBC announced it would conduct a pilot study for a retail CBDC, the Digital Currency and Electronic Payment (DC/EP) project. On 20 April 2020, a PBC spokesperson confirmed that pilot testing was under way in several cities: Shenzhen, Suzhou, Chengdu, Xiong'an and the "2022 Winter Olympics Office Area" in Beijing (Cheng (2020)).

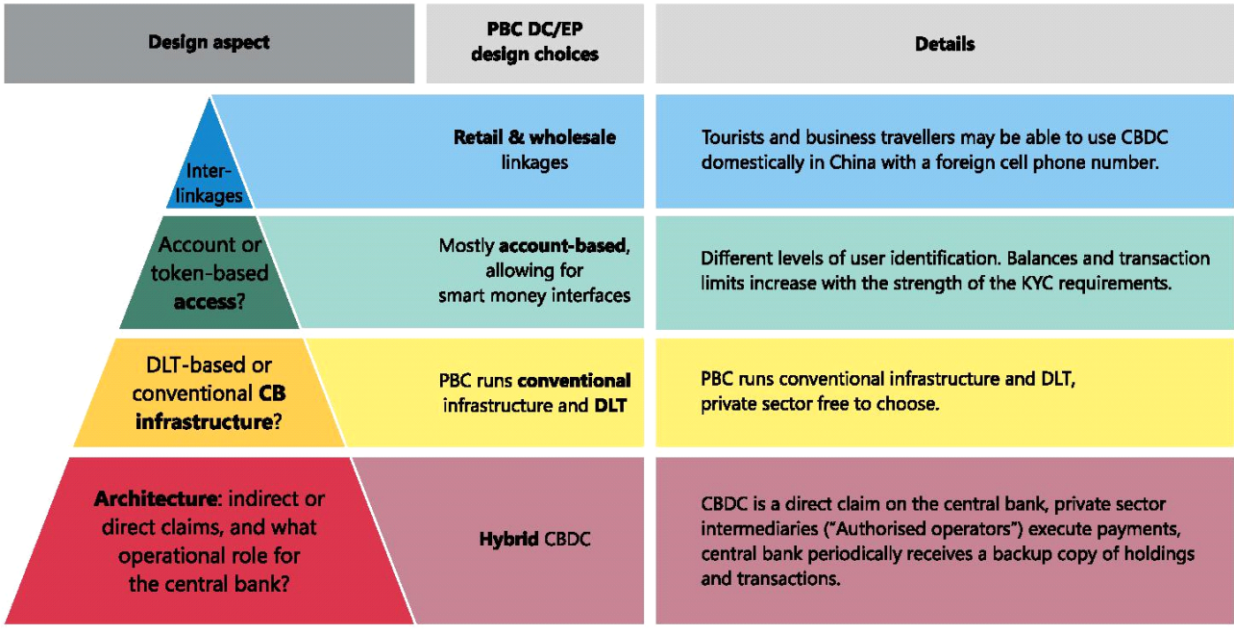
In China, the introduction of a CBDC should be seen in the context of a highly digitised economy and widespread use of private digital payment services. The introduction of a CBDC in the world's most populous country and second-largest economy may have far-reaching implications. In addition to providing a convenient complement to cash for use in online transactions, a CBDC would also bring more diversity to the current mobile payments duopoly of Alipay and WeChat Pay, which collectively control 94% of the market for mobile payments (FSB (2019)). If there is a decision to go beyond the current pilot stage, the DC/EP will become a complement to M0, which includes banknotes and coins, as well as central bank depository accounts. It is **not intended to fully replace physical cash**.

Graph 8 describes the main design characteristics of DC/EP, following the CBDC pyramid. The **architecture** of the current DC/EP pilot is squarely the "hybrid CBDC" model: it features a CBDC that is a direct claim on the PBC, but onboarding and real-time payment services are operated by intermediaries (called "authorised operators"). The central bank periodically receives and stores a copy of retail holdings and transactions.

Fan (2020) emphasises that the role of the PBC is to provide the core infrastructure, while intermediaries such as commercial banks, other payment service providers and telecoms would provide services to the public. This approach prevents concentration of risks at the central bank, disintermediation of existing financial institutions, and duplication or waste of resources given the existing IT infrastructure, processing capabilities and qualified staff at intermediaries.

The backbone of the DC/EP's **infrastructure** would be a mixed system with conventional database and DLT. PBC has, however, emphasised that DLT is not yet sufficiently mature for such a large-scale application. To settle transactions, any system has to be able to accommodate 300,000 transactions per second (TPS) to accommodate the large retail transactions in China.

Design characteristics of the PBC's DC/EP project (pilot phase) Graph 8



Sources: Adapted from Auer and Böhme (2020) and conversations with PBC staff.

The PBC does not require intermediaries to use any specific infrastructure or any specific technological path. However, for transaction records and reconciliation, DLT may be used. The financial intermediaries would remain responsible for know-your-customer (KYC) checks and retail services. Nonetheless, the CBDC would be a direct claim on the central bank, denominated in renminbi.

Regarding **access**, PBC has decided to use a value-based, semi-account-based and account-based hybrid payment instrument. Identity would be based on "loosely coupled account links", such that users could use DC/EP anonymously with counterparts in daily transactions, but that "*operating agencies should submit transaction data to the central bank via asynchronous transmission on a timely basis*" (Fan (2020)). This would ensure that users remain anonymous to each other, but allow the central bank "*to keep track of necessary data to implement prudent regulation and crack down on money laundering and other criminal offences, as well as easing the workload for commercial banks*" (Fan (2020)).

Wallets are based on multiple forms of identification (ID), not all of which need to include the name and other personal information. In particular, they could accommodate tokens or accounts by intermediaries and allow individuals to decide whether to connect to a bank account. To accommodate different levels of user anonymity and access, there would be several grades of digital wallets based on the strength of the KYC levels, with stronger KYC requirements associated with higher transaction limits. Limits would generally be linked to existing rules of use of banknotes and coins; details have, however, not yet been established.

Finally, regarding **international interlinkages**, the DC/EP would be connected to existing retail and wholesale systems, including the RTGS system. The primary aim for DC/EP is domestic retail use. Nonetheless, if an understanding can be reached with foreign jurisdictions, non-residents (eg tourists and business travellers) could

access the DC/EP with a foreign cell phone number for an entry-level wallet. PBC would work to ensure ongoing compliance with relevant AML/CFT rules.

Looking further into the future, the DC/EP could potentially be used for renminbi-invoiced trade with foreign parties, but this is still subject to consultation with other central banks and entities. With a proof-of-concept finished and the pilot under way, the groundwork has been laid: initial testing involves the commercial banks, payment service providers and other private sector institutions. All the authorised operators have formulated an exit plan as part of the pilot programme, similar to a "sandbox" model, to ensure that the process is reversible. The exact launch date remains unclear.[21] In international discussions, representatives of PBC noted that cross-country coordination can be useful to ensure consistent standards across borders. Forums such as the CPMI and Financial Stability Board (FSB) were mentioned as suitable settings for cooperating with other central banks, regulators and public authorities.

Riksbank: the e-krona project

Another advanced CBDC project is that of Sveriges Riksbank, the world's oldest central bank. In Sweden, another highly digitised economy, cash use has been on the decline for some years, to the extent that an increasing number of shops are no longer accepting cash at all. Noting that its economy is witnessing "the greatest and fastest decline in cash worldwide" (Riksbank (2019)), the Riksbank was at the global forefront of discussing the possibility of issuing a CBDC (see Skingsley (2016); Ingves (2017)).

The Riksbank – like other central banks – has researched several technologies and approaches (see Sveriges Riksbank (2017)). Currently, it is developing a proof-of-concept of the e-krona project (see Sveriges Riksbank (2020)). Again, a CBDC would be intended as a complement to, not a replacement for cash.

The **architecture** of the current Riksbank proof-of-concept is a Hybrid CBDC (Graph 9). The CBDC is a direct claim on the Riksbank and payments are operated by payment service operators.[22] On the specific design, Riksbank researchers Armelius et al (2020b, p. 87) note that the ongoing pilot is a "decentralized database of all e-kronor in circulation at any given moment, where the Riksbank verifies all transactions before completion." They classify this under the label "Decentralized solutions with intermediaries", noting also that such designs would require the Riksbank "to provide a contingency solution if one or several intermediaries fail in order to prevent a situation where a substantial numbers of end users are unable to make e-krona payments" (see p 89).

The **infrastructure** and technical implementation are based on DLT using R3's Corda, to run with several notaries. Owing to the proof-of-concept nature, all are currently under the control of the Riksbank and its technology partners.

When it comes to the **access** technology, the CBDC in the Riksbank's pilot is account-based, but an option for low-value token-based prepaid cards is considered. In the ongoing pilot model, the Riksbank issues CBDC but they are stored in wallets

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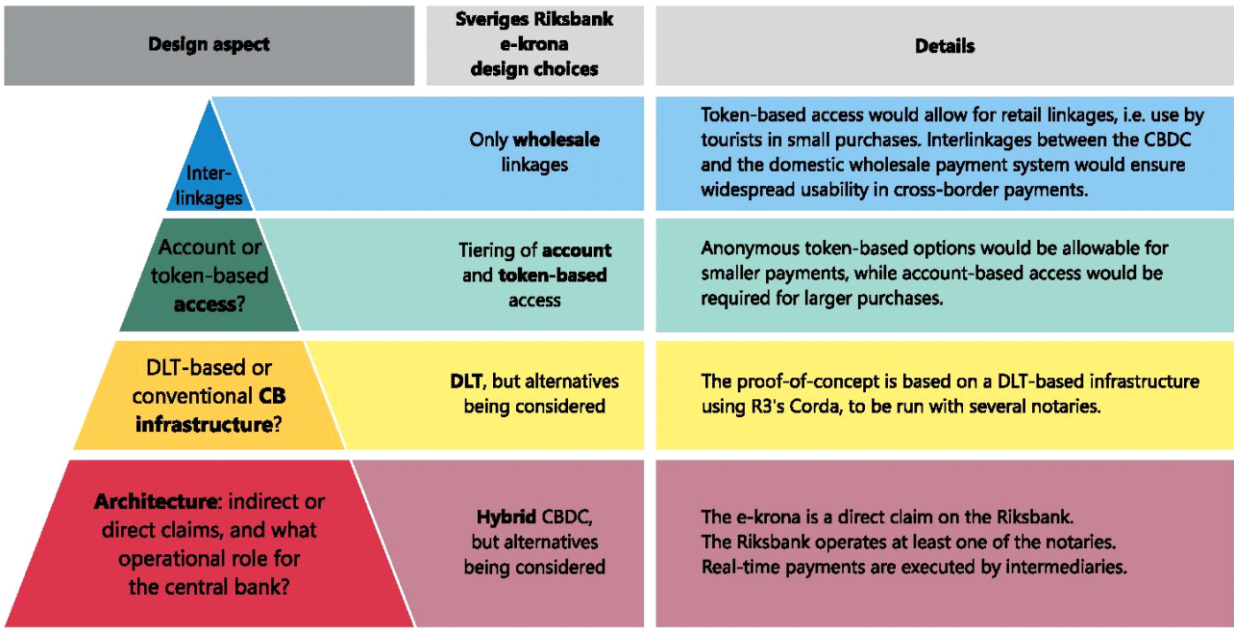
[21] On 15 April 2020, screenshots of the testing wallet for Agricultural Bank of China (ABC) were released in the media (Ledger Insights (2020)).

[22] An earlier report on the e-krona had also considered the Direct option, labelled as "register based e-krona with significant Riksbank commitment" (Riksbank (2017)).

at intermediaries. Access to the wallet is based on identifying the owner of the wallet. Looking ahead, the Riksbank may also develop CBDC payment cards that can be used directly for small value payments and without accessing a wallet (ie token-based access).

It is also noteworthy that even with account-based access, the design will be such that users remain anonymous vis-à-vis the Riksbank. On the one hand, intermediaries are responsible for KYC and ongoing due diligence for each and every CBDC user. On the other, the Riksbank only receives information on individual account balances and payments, but no information on the actual account holders (ie the persons or firms who are behind each account or payment).

Sveriges Riksbank's e-krona (proof-of-concept) Graph 9



Sources: Adapted from Auer and Böhme (2020) and conversations with Sveriges Riksbank staff.

Beyond the current proof-of-concept, a wider range of designs are under consideration. The Riksbank itself has not communicated a view on the preferred technological architecture, other than that the e-krona would be a direct claim on the Riksbank (ie the indirect/synthetic model is not considered). However, its researchers, writing on their own behalf, have considered more detailed options. For instance, when it comes to architectures, Armelius et al (2020b) discuss the policy trade-offs from a centralised model without intermediaries, a centralised model with intermediaries and a Synthetic (Indirect) model. On the latter, they argue that "it is not clear if this should really be considered to be a CBDC", as it is not a direct claim on the central bank (Armelius et al (2020b), p 89). These researchers, however, also judge that even for the Hybrid and Intermediated models, the level of involvement of the Riksbank and the costs of running the system would still be substantial. Beyond the architecture and the technological and access side, both conventional and DLT-based technologies are being considered. Armelius et al (2020b) discuss the relative merits of open source code and licensed proprietary technology. A key requirement

for the actual CBDC will be good offline properties – among others via the above-discussed low value prepaid cards.

Regarding **interlinkages**, the focus on the e-krona is domestic, and retail use by non-residents would only occur via the use of pre-paid cards by tourists for small purchases. On the wholesale side, the CBDC will connect to the banking system and also the RTSG, thus enabling cross-border payments.

Bank of Canada: CBDC as a contingency plan

The Bank of Canada has produced an outstanding body of research and policy communication on the topic of digital currencies. Wilkins (2016) was among the first high-level policy makers arguing for CBDC, and research by staff was actively researching this and related issues early on.[23]

Despite its early start, the Bank of Canada has not communicated that it is developing a retail CBDC pilot or proof-of-concept. Instead, it has outlined a comprehensive plan for the conditions under which Canada should develop a CBDC. It also has set out potential architectures, and it has accumulated relevant technical knowledge through a series of projects on novel payment technologies, also in cooperation with other central banks (see, for example Bank of Canada (2017)). Indeed, as noted by Lane (2020) in February 2020:

> "*we have concluded that there is not a compelling case to issue a CBDC at this time. Canadians will continue to be well-served by the existing payment ecosystem, provided it is moderni[s]ed and remains fit for purpose […] All this being said, the world can change very quickly. The Bank of Canada can imagine scenarios in which we would consider issuing a CBDC so we can continue to provide Canadians with trustworthy methods of payment.*"

In particular, the Bank of Canada has considered (i) a scenario in which the use of physical cash is reduced or eliminated altogether, and (ii) a scenario in which a private cryptocurrency or stablecoin makes substantial inroads as a means of payment. In order to prepare for these eventualities, the Bank of Canada is conducting stakeholder engagement discussions, working with universities and firms on the design of a CBDC. It is also cooperating internationally as part of an international working group on CBDCs.

If a CBDC is to be developed, the overall aim of the design is a digital claim on the Bank of Canada that closely mimics the properties of physical cash, to the extent this is possible. The CBDC would not replace cash, but designed as a digital addition with advantageous resilience and accessibility features.

Because the overall design goal is sufficiently clear, the Bank of Canada has also spelled out elements of the **architecture** (Graph 10).[24] For one, a CBDC would be "a claim in Canadian dollars against the Bank of Canada" (Shah et al (2020)), ie the Indirect/Synthetic approach is not being pursued. Rather, the analytical note lays out

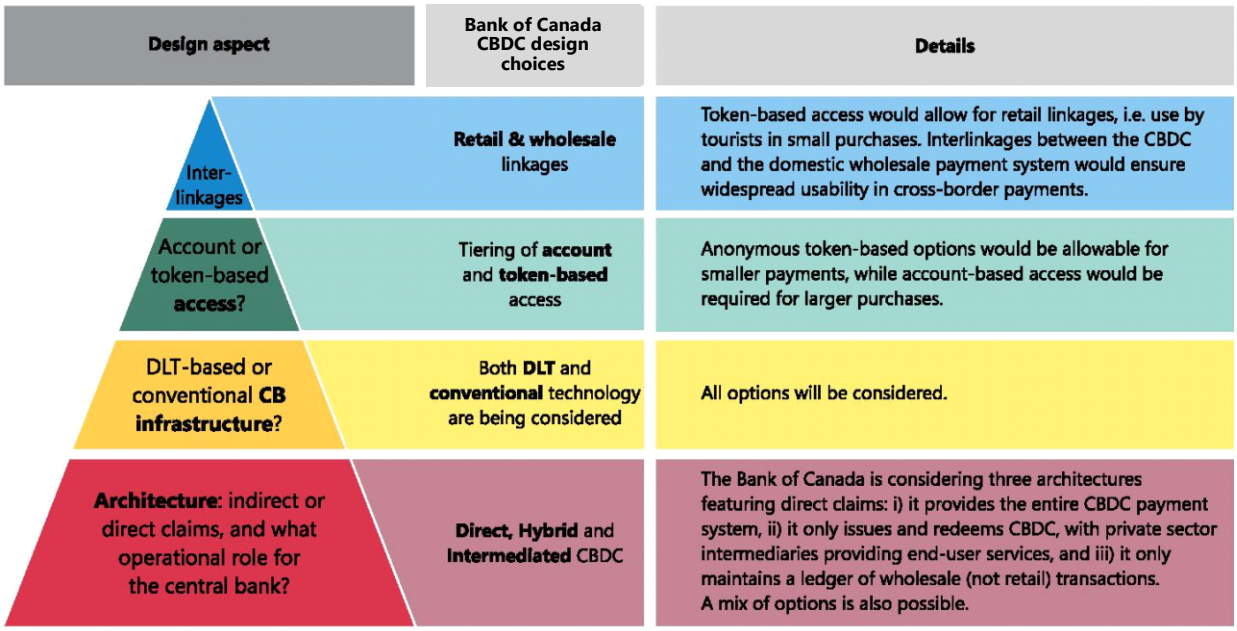
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[23] See, among many others, Chiu and Wong (2014, 2015) on e-money, Fung and Halaburda (2016) on a first assessment of the pros and cons of issuing CBDC and Kahn et al (2018) for an in-depth investigation of desirability and associated design choices, and Davoodalhosseini (2018) for an assessment of the implications for monetary policy.

[24] Bank of Canada refers to the architecture as "Models" or "Business models" in all their communications.

three potential architectures that correspond to the "Direct CBDC" (the Bank of Canada providing the entire CBDC payment system) and the "Hybrid CBDC" (the Bank of Canada only issuing and redeeming CBDC, with private sector intermediaries providing end user services) or the "Intermediated CBDC" (identical to the Hybrid model, where the Bank of Canada does not have access to the full ledger of retail transactions). There is also the possibility of providing a Hybrid option in which intermediaries execute the majority of payments, but the Bank of Canada can conduct some retail payments directly in line with social goals. The goal of the latter approach is to benefit from the valuable services offered by payment intermediaries, but at the same time have available a directly operated option to serve public policy goals such as universal access.

Bank of Canada's CBDC contingency plan — Graph 10



Sources: Adapted from Auer and Böhme (2020) and conversations with Bank of Canada staff.

Details of the **infrastructure** have not been spelled out thus far. The Bank of Canada has experience with a number of novel DLT-based proof-of-concept payment projects. However, it notes that, whereas DLT may be possible as a solution for an infrastructure, it is by no means necessary. Multiple technologies will be considered simultaneously and winners will be picked based on performance.

Both account and token-based **access** solutions will be considered, likely with tiering: anonymous token-based options (including but not limited to value cards) would be allowable for smaller payments. This could be achieved through a low-cost dedicated universal access device (UAD) (Miedema et al (2020)), which could allow users without a smartphone to use the CBDC. Account-based access would be required for larger purchases. As regards the details of such tiering, in particular when it comes to enforcing proper AML/KYC standards, the current level of enforcement as achieved with cash is the model. The tiering will be chosen such that AML and related issues are not graver than is currently the case. Given the new options for illicit use

opened by programmable money, achieving the same level of enforcement might require a reduction in the definition of what constitutes a "large" payment.[25]

On retail **interlinkages**, while the CBDC's focus would be domestic, the option for token-based CBDC naturally makes the system accessible to tourists and other non-residents for making low-value payments. Again, the overall design of the system will be such that issues regarding international use and circumvention of foreign capital controls are no graver than is the case in the current cash-based system.[26]

On wholesale linkages, Bank of Canada will ensure that CBDC will be interoperable with all other payment means, so that it can be exchanged freely with bank deposits and cash. The CBDC will also link directly to the Large Value Transfer System, which handles wholesale payments. Due to the manifold interlinkages with the domestic payment system, all linkages of these systems with foreign payment systems will also be guaranteed.

6. Conclusion

This paper has examined the rise of central bank digital currencies, a new payment technology that may soon be available in a number of countries around the world. We have presented a novel CBDC project index (CBDCPI). We have shown that this index is higher in jurisdictions with higher mobile phone usage and higher innovation capacity. Especially retail CBDCs are more likely where there is a larger informal economy, and wholesale CBDCs are more advanced in economies that have higher financial development. We have also noted that CBDC projects differ starkly across countries, both in their motivations and their economic and technical design. Many central banks are pursuing models where a CBDC is a direct claim on the central bank, but with private intermediaries. To better understand these differences, we have zoomed in on three advanced cases, namely those of the People's Bank of China, Sweden's Riksbank and the Bank of Canada.

Given the novelty of CBDC, and the scope for "clean-slate" thinking on the nature and provision of money, it is natural that the approaches will differ across countries, in line with economic circumstances and users' priorities. In countries where digital payments are already very advanced, and cash use is declining, central banks may respond in particular to ensure the ongoing availability of a public sector-provided means of payment. In countries with a lower penetration of digital payments, financial inclusion may be an important driver. The choice of architectures, infrastructures, access and interlinkages will be tailored to fit local circumstances.

Yet our overview has also shown some key common features. In particular, none of the designs we survey is intended to replace cash; all are intended to complement it. Most still involve a strong role for intermediaries – although potentially in parallel to direct provision of some services by central banks. None of the designs is pursuing the Indirect model, where a CBDC is a claim on intermediaries rather than on central banks. We believe that by sharing information on the drivers, approaches and

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[25] The current definition of cash transactions reportable to FINTRAC is CAD 10,000 (in a single payment or successive payments within 24 hours).

[26] Currently, when travelling to Canada, amounts of foreign currency exceeding a value of CAN 10,000 or more must be reported to customs officials at the Canadian border.

technologies, central banks can learn from one another, thus complementing international policy work in this area.

Going forward, events such as the Covid-19 pandemic highlight the value of access to diverse means of payments, and the need for any payment method to be both inclusive and resilient against a broad range of threats, just as cash is (see Auer et al (2020)). While it is difficult to anticipate the range of challenges ahead, central banks will continue to take a long-term view and carefully consider the role of CBDCs in a range of potential future scenarios.

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Annex A: data collection for CBDC indicators

This annex gives a description of the construction of the CBDC project index (CBDCPI), and our central bank speech stance and search interest scores.

The **CBDCPI** is constructed based on an update to the list of retail CBDC projects identified in Auer et al (2020a) with the addition of a number of project announced after March 2020 and of wholesale CBDC projects. Each published report can take a value of 1 for research reports, 2 if a pilot has taken place or is ongoing and 3 in the (so far hypothetical) case of a live CBDC. We consider only jurisdictions that have a central bank or monetary authority. For each jurisdiction, the overall index is the maximum of the retail and wholesale sub-indices. For China, given lack of material translated into English and considering its prominent role in this field, we have defined a project score of 2. For Australia and the United States, we have defined a project score of 1, given the confirmation of such work in reporting to the Australian Senate by the RBA (2019), and in Congressional testimony by Chairman Powell (2019) and in speeches by Governor Brainard (2020a, b). For the euro area, given the work by both the ECB and several national central banks of euro area countries, we include an observation for the euro area as a whole (with a project score of 1), and each of the 19 euro area members (with 0 or 1 depending on whether the national central bank has published any CBDC research). Empirical results are robust to dropping individual euro area members. For the Eastern Caribbean Currency Union (ECCU), served by the Eastern Caribbean Central Bank (ECCB), the eight member states are included as a single observation with a CBDCPI of 2 given the ongoing pilot. The countries of the West African Economic and Monetary Union (WAEMU) are consolidated into one observation (CBDCPI of 0), as are the members of the Economic Community of Central African States (ECCAS). Full links to public sources are available as part of the background documentation.

The **search interest** score is estimated using a simple average of the interest score for the keywords "CBDC" (search word) and "Central Bank Digital Currency" (topic) over the period January 2013–mid July 2020. The resulting two values for each country are averaged to arrive at the sub-index. For China, we used the Baidu index for keywords "Central Bank Digital Currency" and "DC/EP". We rescaled the values to make them comparable to Google Trends figures (ie values range between 0 and 100) and applied the same procedure described above.

The **central bank speech stance** score is obtained by classifying the stance of each central banker speech containing at least one keyword from the following list: "CBDC", "Central Bank Digital Currency", "digital currency" or "digital money" (with a manual check to ensure it refers to CBDC and not private digital currencies). Speeches come from the BIS central bankers' speeches database (www.bis.org/cbspeeches/), a comprehensive database collecting central bankers' speeches as published on the BIS website for a wide selection of central banks and international organisations. At the time of writing, the database counts 16,036 speeches, covers a period of more than 23 years (1997-current) and has a wide geographical coverage (108 countries and 125 institutions). A query yielded a set of 138 speeches that contained at least one of the keywords of interest. The resulting sample covers the period December 2013–May 2020 and 38 countries including the euro area and several of its member countries. When the speaker was an ECB official we labelled the speech as euro area. Conversely, if the speaker was an official of a national central bank member of the Eurosystem we labelled the speech as the

corresponding country. For China, given the scarcity of material translated into English, we complemented the results with public sources, including Fan (2020).

After compiling relevant speeches, we went through each and classified them by interpreting the stance of the speech towards adoption of CBDC or CBDC more in general. Each speech score can take a value of either –1, 0 or +1 according to the specific speech stance. The score takes a value of –1 if the speech stance was clearly negative or in case it was explicitly said that there was no specific plan at present to issue digital currencies. It takes a value of 0 in case of a neutral stance. Finally, it takes a value of +1 if the speech stance was clearly positive or a project/pilot was launched or was in the pipeline. Finally, the speech score was calculated as a simple average of the country level scores. If a country did not have any speech score, we replaced the missing values with a zero, is in line with the interpretation of a neutral stance.

In the total sample of 175 countries or currency areas (ie euro area for ECB-related activities, Eastern Caribbean for the Eastern Caribbean Central Bank and WAEMU and ECCAS for these currency unions), 55 had a non-zero value for either the CBDCPI or one of the two underlying scores. In the other 120 countries or currency areas without any communication on CBDC, CBDCPI takes the value of 0.

The full data set is made available with the paper.

Annex B: overview of CBDC projects

Selected retail CBDC projects — Table B1

Design choices				Project/country	Notes on status, motivation and conclusion
Architecture[1]	Infrastructure[2]	Access[3]	Interlinkages[4]		
D	U	A	N	Rafkróna Iceland	Research; Aim to address "steadily diminishing use of banknotes and coin"; "many issues have yet to be clarified, and they must be dealt with appropriately before a position can be taken".
D	U	A	N	Sand Dollar The Bahamas	Pilot; Improve "financial inclusion […], [reduce] the size of legitimate but unrecorded economic activities, [strengthen] national defences against money laundering and other illicit ends [and][…] deliver government services through digital channels, thereby improving tax administration and increasing the efficiency of spending".
D	U	U	N	"E-krone*" Denmark	Research; "the potential benefits of introducing CBDC are not assessed to match the considerable challenges that the introduction would present".
D	U	U	N	"E-krone*" Norway	Working group; focus on "independent back-up solution, credit risk-free alternative to bank deposits, competition, legal tender"; "more information is required before a conclusion can be reached".
H or I	C	A	I	"E-euro*" The Netherlands	Research; "The introduction of CBDC does not require the use of DLT."; "opting for CBDC implies trust in the central bank, which is why we have chosen a reference design with a centralised consensus mechanism."; "the technology behind account-based digital payment systems has proven itself to a far greater extent than value-based digital money".
H or I	D & C	A	N	DC/EP (Digital Currency/Electronic Payments) China	Ongoing work; aim to create digital alternative to cash and coins for retail use.
H or I	D	A/T	I	"E-euro*" ECB	Research; "CBDC with the status of legal tender could guarantee that all users have, in principle, access to a cheap and easy means of payment"; "proof of concept also highlights a number of areas where there is room for improvement".
H or I	D & C	A/T	N	"E-dollar*" Canada	Contingency plan; "building, as a contingency, the capability to issue a cash-like central bank digital currency (CBDC) to the public, should the need ever arise."
H or I	D	A/T	N	E-krona Sweden	Pilot; "within a few years, if the current trend continues, we will find ourselves in a situation where cash is no longer generally accepted as a means of payment"; "an account-based e-krona could rationalise payments from agencies and make them less dependent on commercial agents".
H or I	D	T	N	Digital Fiat Currency Brazil	Research; "Improve the efficiency of the monetary function, … payment processes and systems, …. financial inclusion and … user experience". Architecture: Hybrid, as on the one side "any relationship between the Central Bank and society is intermediated by financial institutions, just

					as with physical cash." On the other side intermediaries are only "custodian of the new cash form".
H or I	U	U	U	"E-pound*" United Kingdom	Research; "households and businesses should be able to make fast, efficient and reliable payments, and benefit from a resilient, inclusive, innovative, and competitive payment system."; "two key elements of the platform: (1) a core ledger, provided by the Bank, would record CBDC and process payments, and (2) private sector 'Payment Interface Providers' would handle the interaction with end-users of CBDC and provide additional payments functionality through overlay services".
U	D	T	I	DXCD Eastern Caribbean	Pilot; Aim to address the "high cost of current payment instruments and banking services", needs of customers and inefficient cheque settlement.
U	C	A	N	Dinero Electrónico Ecuador	Pilot; "means of payment available to absolutely all Ecuadorians". Operated 2014–16; discontinued.
U	D	U	N	Bakong Cambodia	Pilot; aim to "increase access to quality formal financial services"; "decrease demand for… cash".
U	D	U	N	E-hryvnia Ukraine	Pilot; Test DLT "as a technological framework for e-hryvnia issuance and circulation"; no fundamental advantage in using DLT in a centralised model.
U	U	T	N	Electronic legal tender South Africa	Expression of interest; "The scope of this project is specific to the use of a CBDC as electronic legal tender (ELT), similar to the characteristics of, and complementary to, cash."
U	U	U	I	"E-euro*" France	Research; "[…] account based model would offer better results for a retail CBDC. However, it might also lead to a greater loss of resources for banks […]".
U	U	U	I	"E-euro*" Spain	Research; "The case of non-anonymous CBDC based on technology similar to the current electronic payment methods would imply significant infrastructure costs and operational and regulatory requirements".
U	U	U	N	Billete Digital Uruguay	Pilot; "Digital bills that aim to have same functions and uses as physical bills"; ongoing evaluation.
U	U	U	N	E-shekel Israel	Research; "help in the struggle against unreported transactions"; "contribute to the high-tech sector (fintech)"; Conclusion that "the team does not recommend that the Bank of Israel issue digital currency (e-shekel) in the near future".
U	U	U	N	CBDC series New Zealand	Research; "Safer and cheaper to transport than cash"; "Provides public access to an electronic form of legal tender"; "Reduces cash demand and supply which could reduce the availability of cash in an electricity outage"; "Slow payment authorisation in a blockchain-like crypto-currency".
U	U	U	N	"E-lilangeni*" Eswatini	Research; "evaluate whether clear use cases exist for the introduction of a retail and/or wholesale CBDC specifically within the context of Eswatini. Findings from the first phase of investigation indicate that there are indeed at least three potential use cases". "However, while these results are positive, further research is warranted…".
U	U	U	N	"E-rupiah*" Indonesia	Research.
U	U	U	N	"E-ringgit*" Malaysia	Research; "Pioneering work reviewed generally concludes that CBDC, even if introduced in the future, would likely be a complement rather than a substitute to cash and bank deposits". "Technological hurdles need to be considered, as central bank credibility must take priority".

U	U	U	U	"E-won*" Korea	Pilot; Start researching and reviewing technology, process, legal framework. Test if CBDC will technically work in a limited environment.
U	U	U	U	"E-dinar*" Tunisia	Research.
U	U	U	U	"E-rouble*" Russia	Research.
U	U	U	U	"Digital-dollar*" United States	Research. "…the opportunities and challenges of, as well as the use cases for, a CBDC, as a complement to cash and other payments options".
U	U	U	U	"E-AUD*" Australia	Research. "… the case for issuing a CBDC for use by households has not been established"; "… the implications of CBDC for the structure of the financial system would need to be carefully considered".
U	U	U	U	"Digital-Yen*" Japan	Research.
U	U	U	U	E-franc Switzerland	Research; "Examine the opportunities and risks of introducing a cryptofranc (e-franc)"; "additional benefits currently low, outweighed by risks".

[1] D = Direct; H or I = Hybrid or Intermediated; U = unspecified or multiple options under consideration. [2] C = Conventional; D = DLT; U = unspecified or multiple options under consideration. [3] A = Account-based; A/T = tiering of Account- and Token-based; T = token-based; U = unspecified or multiple options under consideration. [4] I = International; N = National; U = unspecified or multiple options under consideration. * Not an official designation by the central bank.

Sources: central banks' websites; conversations with central bank staff; www.centralbanking.com; www.unescap.org; www.efd.admin.ch.

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