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NOTES

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Executive Summary

The payment system is evolving rapidly, with new forms of digital currencies providing opportunities, while fueling debates, including on the environmental costs.[1] Whether through the printing, distribution, and disposal of cash or through the processing and maintenance of card or bank payments, there is an energy and environmental cost to payments, which is nonnegligible. But the payment system is in motion. One key part of the payment system transformation is the rise of crypto assets that rely on cryptography and distributed ledger technologies (DLTs). This paper examines the implications for energy consumption from different forms of crypto assets based on their distinct design elements. It investigates how the takeaways from this evaluation can inform the design of environmentally friendly central bank digital currencies (CBDCs).

The energy consumption of crypto assets can vary greatly depending on two design elements of the supporting DLT network. The first element is the consensus mechanism used to achieve agreement about the present state of the network. Resulting energy needs range from very intensive, as in the case of proof-of-work (PoW) algorithms, such as the one used in Bitcoin, to orders of magnitude lower energy consumption when non-PoW mechanisms are used. The second element is the level of control that can be exercised on the underlying architecture (for example, control over the number of nodes, ability to assign roles to participants, location of the nodes, and ease of updating code). Compared to permissionless systems that allow anyone to join as a validator, permissioned networks allow for stronger controls on parameters that influence the energy consumption of the core processing infrastructure.

Some design options implemented by crypto assets can allow for higher energy efficiency compared to the current payment system. Academic and industry estimates indicate that non-PoW permissioned networks are significantly more energy efficient than current credit card processing centers, in part because the latter involve energy-inefficient legacy systems. Moreover, these crypto assets can further improve on the traditional payment system in terms of energy consumption because they employ purely digital solutions rather than physical means of payments (such as cash or cards and terminals).

CBDCs could also be designed to use infrastructures that are less energy intensive than the current payment system. CBDCs that rely on non-PoW permissioned networks could harness the efficiency gains from those networks and from relying on digital means of payments. Depending on the number and location of the nodes of a particular design, CBDCs could further optimize energy use. Non-DLT CBDCs could also be more efficient than the current payment system if central banks select the platform, hardware, and other elements of the CBDC ecosystem with energy efficiency as a criterion.

Such potential for a positive environmental impact will also depend on additional factors. Regulation and compliance costs, for instance, can be an important source of energy spending. It will also depend on whether and how additional features, not commonly part of crypto assets, are deemed necessary for CBDCs, such as increased resilience measures or offline capabilities. Methodologies and data for the full assessment of the payment chain are currently a work in progress.

1 In the context of this paper, the term "digital currencies" refers to crypto assets and CBDCs.

I. Introduction

Payment systems are undergoing rapid change worldwide. New entrants challenge the role of incumbents, legal frameworks are evolving, and technological advances offer new possibilities along with new concerns. In particular, the growing use of digital currencies plays an important role in these changes. Digital currencies include crypto assets and central bank digital currencies (CBDCs).[2] The long-run evolution of the demand and the regulatory environment for digital currencies remains uncertain, but the prospect that digital currencies can come to play a prominent role in the payment system is material.[3]

BOX 1. Definitions

- *Central bank digital currency:* A digital payment instrument, denominated in the national unit of account that is a direct liability of the central bank.
- *Consensus mechanism:* Algorithm by which various parties reach an agreement. In DLT, those rules allow nodes to agree on the status of the network and maintain consistent copies of a single data set.
- *Crypto assets:* Digital assets that are privately issued using DLT and cryptography to ensure their integrity. Their value can be market based (for example, Bitcoin) or pegged to another asset or pool of assets, such as stablecoins (for example, USD Coin).
- *Distributed ledger technology (DLT):* Digital systems in which information is accessed, validated, and updated jointly across a network of nodes. DLT refers to various technologies, including blockchain in which the data is updated in blocks of transactions that are chronologically chained together through cryptography.
- *DLT nodes:* Instances of software participating in a DLT network. Depending on the specific implementation and parameters, nodes can actively participate in the consensus mechanism and store parts or the entirety of the ledger.
- *Permissionless DLT (also known as "open DLT" or "public DLT"):* A ledger in which anyone may participate in the consensus protocol, as no central authority can approve or deny participation. Permissionless DLT applications usually rely on monetary incentives.
- *Permissioned DLT (also known as "closed DLT"):* A ledger in which the consensus protocol requires participants to be certified by an entity, or by a consortium, prior to connecting to the network to read, write, or validate transactions.
- *Proof of work (PoW):* Mechanism of presenting evidence of a specific computation. In the Nakamoto consensus, this process is central to determining valid blocks in a distributed ledger. Typically, expected rewards are directly proportional to the computing power of participating nodes.
- *Stablecoins:* Crypto assets that aim to maintain a stable value relative to a specified asset or a pool of assets.

[2] The term "currency" is not used here in the legal sense, which refers to "the official means of payment of a State/monetary union, recognized as such by 'monetary' law" (Bossu and others 2020).

[3] In particular, IMF (2020) discusses global adoption scenarios of CBDC and stablecoins. The demand for stablecoins may also accelerate because of the adoption of new decentralized financial services (DeFi) for which they provide liquidity. DeFi is the term used to describe decentralized applications or protocols running generally on a blockchain network whose purpose is to provide financial services to crypto asset investors (Castro-Iragorri and others 2021).

Payments come with an environmental footprint, and it is important to understand how digital currencies may affect this. Existing payment systems, such as cash and credit cards, are known to consume nonnegligible amounts of energy (Annex I). For digital currencies, a large variance in energy costs is associated with different technologies. This paper scopes this diverse landscape, standing at the intersection of IMF work on Fintech and IMF work on climate change. The paper leverages existing studies on the energy consumption of various digital systems that are used or considered to be used as a core infrastructure for digital currencies. As part of this scoping exercise, the paper recognizes, first, that energy metrics provide only a partial assessment of environmental impact (Box 2); second, that with a potential growing use of digital currencies, policymakers face multiple trade-offs that are not related to environmental concerns and lie outside the remit of this study; and, third, that the category of digital currencies encompasses an array of instruments that differ in many dimensions, only a few of which are covered in this paper.[4]

The rest of the paper is organized as follows. The next section provides an overview of the components of payment systems and compares the features of traditional systems with those based on digital currencies. Section III analyzes the elements and design features that influence the energy consumption of different types of crypto assets. Section IV considers the implications of this analysis for the design of an environmentally friendly CBDC.

BOX 2. Assessing the Environmental Impact of Payment Systems

Although this paper focuses on the energy consumption of digital currencies, a more complete study of the environmental footprint of any technology would involve more elements:

- A life cycle analysis would consider the impact of products and services from their conception to their disposal. Therefore, in the case of digital infrastructure, in addition to the direct energy cost related to processing, there are other relevant factors such as the production of servers, the people involved in the organizations, and waste. However, methodologies and data to conduct such analyses are still incomplete.
- An example of an energy cost that could be taken into account is the energy necessary to maintain the underlying networks. Data transfers over the internet require infrastructures such as long-distance communication and routers that require energy to operate (Ahvar, Orgerie, and Lebre 2019). This is particularly relevant in DLT as peer-to-peer activity can have different data traffic profiles depending on the geography of the network's nodes, settings, and algorithms.
- The Paris Agreement requires improvement in both energy efficiency and the amount of carbon emissions per unit of energy consumed. Therefore, the carbon intensity of the energy used should be explored, as well as indirect emissions such as worker commuting or travel, which have been proven to represent a significant part of corporations' emissions (Klaassen and Stoll 2021).[5]
- Beyond greenhouse gas emissions, other examples of environmental factors of importance are the production of hardware, including the use of rare metals and freshwater, e-waste, and the environmental costs of recycling the hardware (Forti and others 2020). Several electronic components can have a damaging chemical impact on landfills.

4 Although several types of digital currencies (Houben and Snyers 2020) exist, for example classified based on whether they are backed (stablecoins) or whether they are used for payments, this paper focuses exclusively on certain aspects of their design: consensus mechanisms and trust, and whether they are private (that is, crypto assets) or issued by the central bank (CBDCs).

5 As standardized by the Greenhouse Gas Protocol, direct carbon emissions are considered the first scope of emissions, carbon emissions from energy consumption constitute the second scope, and indirect emissions are referred to as the third scope.

II. Payment System Components

Payment systems have two main components: core processing and user payment means. Core processing refers to the instructions and operations involved in the processing and settlement of payments. User payment means are the technologies, devices, and actors that enable those payments. Table 1 provides an overview of these components for several prominent traditional payment methods and for digital currencies.[6]

Table 1. Core Processing and User Payment Means Components of Several Payment Methods

<table>
<tr><th rowspan="2"></th><th colspan="3">TRADITIONAL PAYMENTS</th><th colspan="2">DLT-BASED DIGITAL CURRENCIES</th></tr>
<tr><th>CASH</th><th>BANK TRANSFERS</th><th>CREDIT CARDS</th><th>PERMISSIONED</th><th>PERMISSIONLESS</th></tr>
<tr><td>CORE PROCESSING</td><td rowspan="2">Creation, distribution, use, and disposal of banknotes and coins</td><td>Bank data centers, RTGS[7]</td><td>Card issuer and bank data centers, RTGS</td><td>Accredited nodes</td><td>Any node that joins the network to validate transactions</td></tr>
<tr><td>USER PAYMENT MEANS</td><td>Websites, checks, bank branches</td><td>Physical cards and point-of-sale terminals</td><td colspan="2">DLT digital wallets and third-party providers</td></tr>
</table>

In traditional digital payment systems, trusted agencies perform core processing functions and provide the means for user payment access. In bank transfers, the banks oversee the verification and settlement of transactions on their respective ledgers. This process involves their internal data infrastructure as well as potentially several other departments, such as compliance. Additionally, several actors, including central banks, are involved in transferring information and ultimately settling the balances between the banks. Users can perform bank transfers through, for example, bank websites or checks and in person at bank branches; the provision of such payment access points constitutes the layer of user payment means. In credit card payments, the core processing involves the data centers of the card issuer as well as those of the banks. Merchants receive credit card payments on their bank accounts, and users make periodic payments to clear their card balances. Here, user payment means are composed of physical cards and point-of-sale terminals.

In digital currencies that rely on DLT systems, consensus mechanisms underlie the trust in the core processing function, whereas digital wallets are the main means of user payment access. A central feature of DLT systems is that the validation process can be decentralized and shared among a set of validator nodes. This is achieved through a validation and agreement protocol known as the consensus mechanism. The participants validating transactions and the consensus mechanism constitute the core processing of DLT. Among DLT systems, a distinction exists between systems where any participant can take part in the validation, known as "permissionless DLT," and systems where validators are identified and authorized, called "permissioned DLT." In terms of user payment means, DLT-based systems mainly rely on digital wallets. Digital wallets are software used to perform payments that can be used in existing devices, such as cellphones.

6 For cash, Table 1 does not distinguish between core processing and user payment means, because it is a physical token provided by the central bank and settled directly among users.

7 Real-time gross settlement (RTGS) refers to systems operated by central banks to settle money and securities between banks.

III. Comparing Energy Use Across Crypto Assets

The energy consumption of crypto assets depends on the design elements of their DLT systems. This section explores two of the most impactful dimensions. The first element is the consensus mechanism used to achieve agreement about the present state of the network. The second element is the level of control that can be exerted on the underlying architecture.

Comparing Consensus Mechanisms: PoW and Non-PoW DLT Systems

The need for high computational power is part of the design of PoW systems, including the one used by Bitcoin, the first and best-known crypto asset. Bitcoin was first minted on January 3, 2009, with the goal of providing digital payments without the reliance on trusted intermediaries. The lack of a centralized authority means that decisions regarding the validity of transactions are delegated to the network of participating users. For Bitcoin, this is achieved through the Nakamoto consensus mechanism using PoW.[8] Anyone can download the free Bitcoin software to make a computer a Bitcoin node that can validate transactions. The probability that a node adds the next group of transactions to the ledger (by forming a "block") depends on the computational power expended on solving an algorithmic challenge. The incentive of validators to add transactions to the ledger is the newly minted coins and transaction fees obtained as reward. The disincentive to add invalid transactions is that the rewards are received only if valid transactions are added, as other nodes can reject blocks that contain invalid transactions. Such rejection implies that the validator incurs a net loss because it has expended computational power and received no reward.

From an environmental perspective, PoW mechanisms have two important negative implications: energy consumption and e-waste. A DLT system based on PoW consumes much electricity in the computations performed by nodes competing for transaction validation.[9] For example, as of April 25, 2022, the annual electricity consumption of the Bitcoin network is estimated at 144 terawatt hours (TWh) per year according to the Cambridge Bitcoin Electricity Consumption Index.[10] This amounts to about 0.6 percent of total global electricity consumption.[11] A second environmental concern is e-waste, which refers to electronics that are discarded at the end of their useful life (Box 2). The reason PoW consensus mechanisms lead to large e-waste is that validators need to constantly upgrade to the latest, fastest hardware to remain competitive. De Vries and Stoll (2021) estimate that the average life span of Bitcoin mining devices is 1.3 years and that as a result the Bitcoin network cycles through 30.7 metric kilotons of equipment per year, roughly equivalent to the e-waste generated by a small advanced economy like the Netherlands.[12]

In non-PoW mechanisms, the probability of adding the next group of transactions (block) to the ledger does not depend on the computational energy expended. In one of the best known examples

[8] Nakamoto consensus is the full procedure by which blocks are selected. It comprises a computational competition, PoW, and a selection rule, in which the chain with the most computations is the valid one. For an initial definition, see Bonneau and others (2015).

[9] The paper does not consider whether energy use has merits in the sphere of crypto assets, such as particular security properties. For an analysis and comparison of consensus mechanisms based on properties other than energy consumption, including security, see Bains (2022).

[10] This index, published by the Cambridge Center for Alternative Finance (CCAF), is the most commonly cited source on Bitcoin energy consumption. Its underlying methodology can be accessed on its website: https://ccaf.io/cbeci/index.

[11] This is comparable to the total annual electricity consumption of Austria and Finland combined.

[12] Considering this e-waste on a per-transaction basis, De Vries and Stoll (2021) find that a single Bitcoin transaction generates an amount of e-waste (272 grams) that is comparable to throwing away two iPhone 13 Minis (141 grams each). Note also that the amount of e-waste depends positively on the Bitcoin price because a higher Bitcoin price incentivizes more intense competition between Bitcoin miners. Hence, if the price of Bitcoin rises over time, the problem of e-waste will worsen.

of non-PoW mechanisms, proof of stake (PoS), this probability depends on the amount of crypto assets "staked." Validators are incentivized to add valid transactions in a timely manner. Otherwise, they risk being punished by losing part of or all their stake.[13]

Figure 1 presents energy consumption estimates for the core processing of different payment systems. Using estimates from private companies and academic studies, this paper compares the energy consumption of payment systems on a per-transaction basis.[14,15] Figure 1 classifies DLT-based payment systems into permissionless PoW, permissionless non-PoW, and permissioned non-PoW.[16] It also reports estimates for credit cards. It should be noted, however, that in a DLT system, the number of payments can exceed the number of transactions. First, multiple payments can be batched into a single transaction. Users and crypto asset exchange companies have incentives to batch payments to save on transaction fees. Second, so-called layer 2 protocols built on top of the blockchain network often aim to increase scalability and transaction speed and to save on transaction costs (Box 3). For example, Bitcoin stands at around 100 million transactions per year, but considering batching and layer 2 transactions, it can be estimated that Bitcoin currently processes approximately 250 million payments per year.[17]

13 The second largest cryptocurrency in total value, Ethereum, is transitioning from PoW toward proof of stake. Although initial ideas were devised in 2014, acceptance, implementation, and deployment are still an ongoing process.

14 As discussed in Box 2, comparisons based on energy consumption could potentially diverge from comparisons based on CO2 emissions. For instance, Bitcoin miners have incentives to locate near cheap energy sources, which may or may not be based on renewable sources. For example, China's recent ban on crypto asset mining led to a large migration of miners. However, the largest beneficiaries have been countries whose share of renewables in power generation is relatively low. It is also worth noting that the use of renewables can involve an opportunity cost: if Bitcoin mining takes up renewables, this may reduce the availability of renewables to replace energy sources for other uses.

15 Analyses conducted on a per-transaction basis are common in the literature (Platt and others 2021; Sedlmeir and others 2020a, b), as they approximate a measure of energy expenditure relative to the utility provided by the payment system at a given moment. Metrics other than the number of transactions might also be relevant for evaluating the respective social value, and payment systems might scale differently as discussed below.

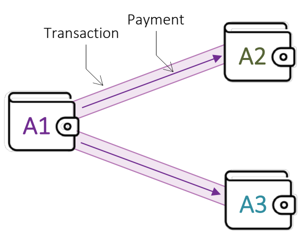
16 Estimates for PoW-based systems, for which energy expenditure is correlated with market capitalization (Sedlmeir and others 2020a), are mostly based on Bitcoin and Ethereum. For non-PoW, projects analyzed include Algorand, Avalanche, Cardano, Hedera, Polkadot, Solana, Stellar, and Tezos.

17 As of March 2022: The Bitcoin network confirms approximately 250,000 transactions per day, which translates to 91.25 million transactions a year. On average, a Bitcoin transaction represents 2.5 payments through batching, which can be evaluated by counting the average number of additional outputs. This leads to a total of approximately 230 million payments per year. For Lightning (the largest layer 2 network on Bitcoin), there are 19,000 participating nodes with active channels (March 2022, Acinq). Assuming each participant makes 2 payments a day (this is the average from the 2020 Survey of Consumer Choice), a rough estimate of an additional 14 million payments per year can be made. Arcane Research provides an estimate of 8 million payments per year. However, the capacity of the Lightning network is vastly larger and could evolve in the future.

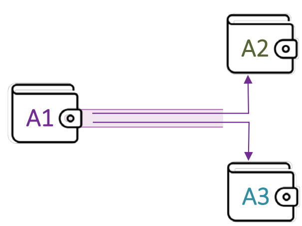
BOX 3. Batching and Layer 2

Blockchain transactions move funds from address to address. In permissionless systems, as transactions are validated, networks require senders to pay fees to validators for their effort. In the diagram below, panel (i) represents different payments made by a user through the same number of transactions. A blockchain transaction may also contain several payments from one user to several users, which is represented in panel (ii), whereby two payments are contained in a single blockchain transaction. This feature enables the reduction of transaction fees paid and is often used, for example, by crypto asset exchanges to pay multiple users withdrawing funds concurrently.[18]

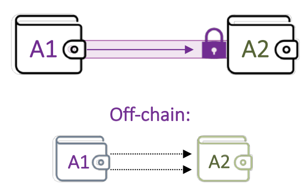
Layer 2 solutions are a set of technologies that scale blockchains and reduce fees by adopting off-chain processing.[19] In general, a user initiates a channel by submitting a set of transactions in the main chain and locking funds for that channel in a smart contract (a program stored on a blockchain that runs when predetermined conditions are met). This channel may be used to make as many off-chain payments as desired. Panel (iii) illustrates this scenario. Such payments are processed much faster, and at a fraction of the fees, compared to the main blockchain. Once the channel has concluded its purpose, a second and final transaction is performed to settle the accounts on the main blockchain. In doing so, transactions in the primary network may represent a large set of payments, which were performed off-chain.



(i) One payment per blockchain transaction.



(ii) Two payments batched in one blockchain transaction.



(iii) A1 locks funds for future payments to address A2. Then, several payments can be processed off-chain. The payments will be settled at a later stage with another on-chain transaction.

Source: Authors.

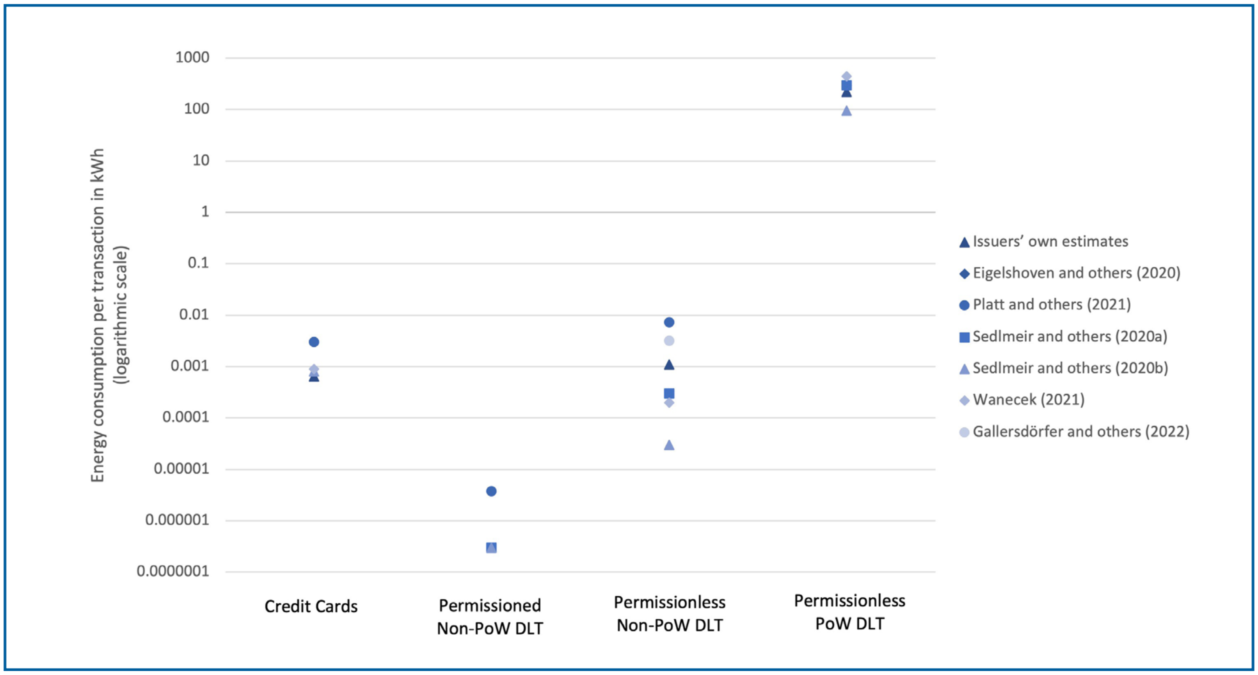
PoW-based DLT systems use many orders of magnitude more energy per transaction than DLT systems that are not based on PoW. There is relatively close alignment among the private sector and academic estimates on the orders of magnitude of the energy involved in transactions based on PoW DLT. Although estimates of the energy cost of different non-PoW DLT applications vary considerably in Figure 1, all these

[18] The fee is proportional to the digital size or the computational intensity of the transaction. Although batched transactions are generally slightly larger than individual transactions and thus more expensive, their cost per payment is lower than individual transactions.

[19] The most popular options for off-chain processing are the Lightning network, plasma chains, and ZK- and optimistic rollups.

estimates are nevertheless far below those for PoW DLT. Although scalability solutions and increased usage might change the costs per transaction, comparisons are likely to remain valid.[20]

Figure 1. Estimates of Energy Use (in kWh) per Transaction for the Core Processing of Different Payment Systems



Source: Authors' calculations based on academic and private-sector publications.
Note: For the cases in which a source provides multiple estimates, the figure displays the midpoint.

For crypto assets, the energy costs from initiating a payment and displaying confirmations through user interfaces are likely to be small. Estimates in Figure 1 center on the energy use for the core processing operations that underlie crypto assets. Separate estimates of means of payments in crypto assets are not available. However, because crypto asset payments center on online payments using digital wallets, these energy costs are likely to be small. Estimates for the energy use of smartphone apps, such as those described in Wilke and others (2013), show that a few minutes of app use (the likely amount of time needed to complete a transaction on a digital wallet) can be measured on the order of 10^{-7} kWh. To the extent that digital wallets resemble other apps in energy consumption, this energy consumption would be considered negligible.

[20] For instance, although Bitcoin's energy expenditure is not directly linked to the number of transactions, an increased usage might still affect its energy cost. The evolution of the energy consumption of base Bitcoin transactions will evolve depending on the mining reward, the level of transaction fees, and the price of the underlying asset. One way to think about this is in terms of an overall demand effect versus a substitution effect. Demand effect: by making crypto assets more attractive as a means of payment overall, and strengthening any network effects, a successful and growing layer 2, as well as batching (see Box 3), would increase the demand for the asset, raise its price, and thus increase mining rewards (as rewards are in Bitcoin). Higher mining rewards raise the incentives to mine and therefore increase energy consumption. Substitution effect: for a given level of the asset transaction demand, layer 2 reduces the demand for on-chain transactions by allowing for more off-chain transactions, which reduces transaction fees (transaction fees depend on the demand for transactions) and the incentive to mine, which would in turn reduce energy consumption. See also Sedlmeir and others (2020a).

Impact of the Control Level Enabled by Permissioned Relative to Permissionless Networks

Besides the consensus mechanism, other factors affect the computational power required to maintain a safe, scalable, and trusted system. Parameters that play an important role in energy use include the number of nodes that constitute the network (Gola and Sedlmeir 2022; Platt and others 2021; Sedlmeir and others 2020a);[21] the relative role of each node (Gola and Sedlmeir 2022; Platt and others 2021);[22] the distance between nodes (Ahvar, Orgerie, and Lebre 2019); the flexibility to update the code and nodes to optimize power consumption; and the ability to impose energy criteria for eligibility to be a participant of the network.

Permissioned DLT networks intrinsically have an advantage over permissionless networks in the control over these parameters. Trust lies at the heart of every payment system. In a permissionless network, trust derives from the fact that the history of a ledger cannot be changed unless enough validators collude purposefully to rewrite it. Consequently, on such networks, trust relies on the existence of many honest nodes, including validators, that makes it too costly for enough of them to collude and defraud the ledger. In the case of Bitcoin, the protocol is designed so that "honest nodes control a majority of CPU power" (Nakamoto 2008), meaning that one would require to co-opt more than half the computing capacity of the validators to rewrite Bitcoin's history. In permissioned networks, trust in the infrastructure is inherent: each validator is authorized and identified by a central authority. Such networks require few nodes to keep a sizable ledger updated and guarantee resiliency compared to the permissionless counterparts. Fewer nodes imply less redundancy, therefore less computing power, and, all other factors being equal, less energy consumption. Moreover, central authorities have the power to promote protocols that are optimized for energy consumption and provide a secure and usable network.

Estimates of energy consumption by existing permissioned DLT crypto assets are below those for permissionless DLT crypto assets. Columns 2 and 3 in Figure 1 distinguish the non-PoW DLT estimates according to whether they pertain to permissioned or permissionless systems. Although there is a wide range of estimates for energy consumption, particularly among permissionless systems, the estimates of permissioned DLT systems are consistently below those for the permissionless ones.

If permissioned DLT systems grow in usage, they may be particularly well positioned to benefit from energy economies of scale. According to Platt and others (2021), the economies of scale of a DLT system will depend on the growth of validators: if the number of validating nodes rises relatively fast as the system processes more transactions, then energy economies of scale will weaken. Conversely, if the number of validating nodes is constant regardless of the size of a DLT system, then the energy economies of scale are strong. Relative to permissionless crypto assets, permissioned crypto assets may have greater potential to take advantage of energy economies of scale. Although in permissionless systems anyone can decide to become a validator node, in permissioned systems the validators are, in general, a list of organizations assigned at the outset of

[21] The larger the number of nodes sending and receiving information and validating transactions, the higher the energy consumption. Platt and others (2021) state that for non-PoW blockchains, the contribution to total energy consumption by redundant operations may be significant. They mention that one way to reduce redundancy is to reduce the number of nodes. Platt and others (2021) argue that DLT systems that use consensus mechanisms that require low computational effort (that is, non-PoW) can be assumed to have validating nodes running on similar types of commodity server hardware, irrespective of the network load. Under that assumption, the overall energy consumption of the protocol depends on only the number and hardware configuration of validator nodes.

[22] Different types of nodes can be involved in a DLT network, depending on the governance of the system or the preference of each participant. Full nodes, which verify the entire history and maintain the current state of the ledger, are the best known. Archival nodes keep the entire copy of the ledger since the first block. Light nodes hold only partial elements of the ledger and are used for simplified payment verification. A full node requires more resources than a light node.

the project, and this list may stay fixed, or change little, as the system matures. There are examples of permissioned crypto assets with a predetermined maximum number of validating nodes.[23]

Implications for Potential Energy Gains Compared to Traditional Systems

The estimates for energy consumption per transaction by non-PoW permissioned DLT are below those for core processing by credit cards. Non-PoW permissioned DLT systems have the lowest energy consumption estimates among the DLT systems in Figure 1. The first column of the figure displays the estimates for the core processing function of credit cards. The focus here is on credit cards because, first, they are the only traditional payment system for which detailed estimates per transaction are available and, second, credit card transactions constitute the majority of digital payment transactions worldwide (Annex I). Here, core processing refers to credit card companies' data centers. All estimates for core processing by credit card companies are above those for permissioned DLT systems.

Various factors complicate this comparison, but these generally serve to widen the difference between the estimates in favor of non-PoW permissioned DLT, relative to credit cards. A comparison between the energy per transaction in the data processing center of a credit card company and the energy per transaction of a permissioned DLT crypto asset suffers from three main limitations. The first limitation is that a payment transaction on a credit card involves actors other than the card issuer, such as the merchant's bank, which receives the payment. Including this factor would raise the estimates of energy consumption for credit cards. The second limitation is that transactions on DLT systems have the potential to batch multiple payments (Box 3). If Figure 1 were represented per payment instead of per transaction, this could lower the estimates for DLT systems. The third limitation is that credit cards currently process many more transactions than crypto assets. An attempt to compare these systems on a similar scale (that is, vastly increasing the number of transactions processed using a non-PoW permissioned crypto asset) would likely lower the estimates for the permissioned DLT systems. As previously discussed, permissioned DLT systems are particularly well positioned to benefit from energy economies of scale.

Legacy systems are likely to contribute to the higher energy consumption of credit card payments. Estimates in Figure 1 position the energy consumption per transaction of the core processing by non-PoW permissioned DLT at a lower level than the core processing by credit cards. However, this difference does not necessarily emanate from the nature of DLT systems as compared to traditional systems. The reason is that many traditional digital payment structures rely on legacy systems. Partial support for the role of legacy systems in raising energy consumption can be found in Tiberi (2021), who estimates the energy consumption of a novel, non-DLT payment system, namely the Eurosystem's TARGET Instant Payment Settlement (TIPS). TIPS is a market infrastructure service launched by the Eurosystem in November 2018 that enables payment service providers to offer fund transfers to their customers in real time and around the clock. Tiberi (2021) estimates an energy per transaction of 4×10^{-5} kWh, which is close to the estimates (just above the upper bound) for permissioned DLT systems in Figure 1. As such, the first two columns of Figure 1 can be interpreted as evidence that, in terms of energy consumption, some new forms of core processing in payments can improve on existing forms.

New payment systems, including digital currencies, also offer the prospect of more environmentally friendly user payment means. Some traditional digital payment means come with forms of user

[23] Hedera Hashgraph's permissioned DLT system was set up such that at most 39 organizations can be admitted as validating nodes (as of February 22, 2022, there are 26 permissioned nodes). Another example of a permissioned crypto asset is Diem, a stablecoin that was proposed and then abandoned by the social media giant Meta Platforms. Diem was intended to operate on a permissioned blockchain where only companies and NGOs that are members of the Diem Association would participate in transaction validation. The validators in a permissioned DLT system do not necessarily have to be organizations. One example is EOS, a crypto asset designed to have at most 21 validators (called block producers) that are appointed by voting coin holders.

payment access that consume considerable amounts of energy. For example, an estimate for credit cards that includes the maintenance of card networks and the physical cards, reported in Annex I, is about two orders of magnitude larger than the estimates that center on credit cards' core processing in Figure 1. Most crypto assets instead offer user payment access through digital wallets, which likely consume relatively little energy. Changes to traditional payment systems could also achieve reductions in energy consumption for user payment means. For instance, some major e-commerce platforms offer digital-only credit cards for purchases on their platforms.

From an environmental perspective, cash can be considered a legacy means of payment. The estimates of Hanegraaf and others (2020), discussed in Annex I, highlight the environmental burden associated with the creation, distribution, and disposal of cash notes and coins. Globally, digital payments have been gaining usage share as a means of payment compared to cash (Khiaonarong and Humphrey 2022). For digital means of payment that use little energy in both core processing and user payment means, such developments could constitute an environmental improvement, although cash may come with other merits that digital forms of money cannot easily replicate (McAndrews 2020).

IV. Implications for the Environmental Aspects of CBDC

Policymakers across countries are considering the introduction of CBDCs. Many central banks are studying CBDCs, whereas some have moved ahead to proofs-of-concept, pilots, or the launch of a CBDC (Annex II). The motivations that central banks have for considering CBDCs and the questions around the implications of introducing them are manifold (Boar and Wehrli 2021; Mancini Griffoli and others 2018). Like in the discussion of crypto assets, the focus here is purely on the energy cost of CBDCs, while acknowledging that this is only one of many relevant considerations to evaluate the desirability of issuing a CBDC. Moreover, this discussion centers on retail CBDCs, which are the closest comparator to the payment methods analyzed in the previous sections. A retail CBDC is a novel payment instrument that is intended for use by consumers and firms and that, depending on its design, can blend various features currently attributed to cash and bank deposits (Agur, Ari, and Dell'Ariccia 2022).[24]

Current CBDC projects are based on non-PoW permissioned DLT or on modernized versions of traditional payment architectures. Annex II lists ongoing CBDC initiatives that have reached the stage of proofs-of-concept and pilots, as well as CBDCs that have already been launched. Where known, the technology chosen for the CBDC is listed. Most CBDC initiatives that have specified a choice of technology include the study of a DLT option, and all DLT-based CBDCs opt for non-PoW, permissioned systems. However, some CBDC initiatives are considering a non-DLT architecture. Such non-DLT CBDCs can be based on existing and sometimes recently updated central bank payment clearance systems. For example, Urbinati and others (2021) suggest the possibility of basing a digital euro on the TIPS system, which was discussed in the preceding section as an example of a modernized traditional payment infrastructure with low energy consumption.

The arguments developed in this paper can be applied to consider the environmental implications of different implementations of CBDCs. This section discusses how CBDCs, both DLT and non-DLT based, can be envisaged to affect the environmental aspects of core processing and user payment means and how this may depend on various design choices.

CBDC Core Processing

Both DLT and non-DLT CBDCs have the potential to entail lower energy consumption for core processing functions compared to prevailing traditional means of payment. In Annex II, the CBDC initiatives that are based on DLT and specify the form of DLT all rely on non-PoW, permissioned systems.[25] Based on the estimates provided in Figure 1, this implies that DLT-based CBDC systems have the potential to consume less energy on core processing than credit cards. Moreover, as indicated by the estimates of Tiberi (2021) for TIPS, this lower energy per transaction would seem to be more closely related to novel systems than to DLT per se. That is, a CBDC that builds on a system comparable to TIPS could, in principle, consume less energy on core processing than credit cards. However, various additional considerations, beyond computational requirements, can affect the ultimate core processing energy consumption of a CBDC.

[24] Instead, a wholesale CBDC is intended for use by regulated financial institutions, with the main aim to facilitate among them a more efficient settlement of payments, possibly including cross-border payments. Wholesale CBDC is not discussed here but note that a CBDC has the potential to improve the efficiency of cross-border payments, including by reducing the number of intermediaries involved (Auer and others 2021; Bank of Canada, Bank of England, and Monetary Authority of Singapore 2018; IMF 2020; Maniff and Wong 2021). This could bear a relation to the energy use involved in cross-border payments.

[25] In most DLT-based CBDC initiatives, commercial banks act as permissioned nodes.

On the one hand, CBDCs may require some more advanced features compared to permissioned DLT crypto assets, which can involve additional energy costs. Additional physical security measures at the central bank and participating institutions, as well as backups of servers and hardware redundancy for higher resilience and availability, are likely to be deemed necessary. Other energy requirements may come from the creation of new divisions or research centers working on CBDCs, as well as bespoke tools and teams to enforce regulatory compliance.[26]

On the other hand, central banks' control over the number and location of nodes could facilitate environmental optimization. With a CBDC based on permissioned DLT, the central bank could control the number, the role, and possibly the location of each node of the network. The nodes could be located where sustainable energy is available or where energy is overproduced and goes unused.[27] For a non-DLT CBDC, similar considerations could apply to the location of the main servers, including cloud systems. The same applies to other elements of the CBDC ecosystem. Even though private permissioned crypto assets could also have control over the location of energy-consuming systems, it is not guaranteed that they would incorporate environmental impact as one of their goals.[28]

Moreover, each new technology introduced by a CBDC project could be analyzed, including its energy consumption merits. Central banks that incorporate an environmental aim in their CBDC development could choose to apply the principles of Green Software Engineering that are applied at various major technology corporations (Manotas and others 2016). This could imply optimizing not only the programming involved in the design of the CBDC ledger but possibly any other layer of the supporting technology stack, application programming interfaces, supporting platforms, or audit programs. Central banks can explicitly adopt energy consumption and carbon footprint as criteria for selecting a platform, hardware, and other elements of the CBDC ecosystem. For example, major cloud service providers are shifting toward renewable sources of energy such as geothermal and hydropower, as well as toward locations with colder climates, to reduce the carbon footprint in generating power. Adding the environmental footprint as a selection criterion of a cloud partner can benefit not only the CBDC project but also any future digitalization project of a central bank. One nuance is that central banks may acquire CBDC technology as a platform provided by private vendors (as outlined by the Technology/Provider column in Annex II) and might not have control over some energy consumption parameters. However, because such technologies are still emerging, central banks may have a window of opportunity to influence their development by inducing competition among vendors on CBDC systems' energy impact.

CBDC User Payment Means

In terms of user payment means, CBDCs could potentially harness some of the environmental benefits of available technologies and devices. A CBDC running on devices already owned by users can reduce the reliance on card payment networks. This includes, for instance, digital wallets available on smartphones or payments on low-energy consumption feature phones.[29] The potential for energy reduction in this respect depends, in part, on whether the user hardware and software interfaces are designed with energy

[26] Much of the research and development underlying the development of the traditional payment methods occurred in the distant past. As such, a more appropriate comparison would be in terms of the variable (for example, annual) energy costs of different payment methods rather than including the research and development costs that come with novel payment methods.

[27] Another possible consideration to optimize is the layout of the network to minimize energy transport costs. For example, nodes can be close geographically or efficiently connected.

[28] It is worth noting, however, that private sector–led initiatives to incorporate environmental goals into crypto assets are emerging, permissioned, and permissionless alike, as the Crypto Climate Accord exemplifies, as well as a recent campaign titled "Change the Code, Not the Climate" by Greenpeace US and Ripple cofounder Chris Larsen.

[29] Several countries are exploring the use of Short Message Services (SMS) or Unstructured Supplementary Service Data (USSD) to facilitate payments with CBDCs when data connectivity is not available.

consumption in mind. It also depends on whether the CBDC is designed to be transacted on low-energy devices or whether it requires other forms of more energy-intensive payment methods.

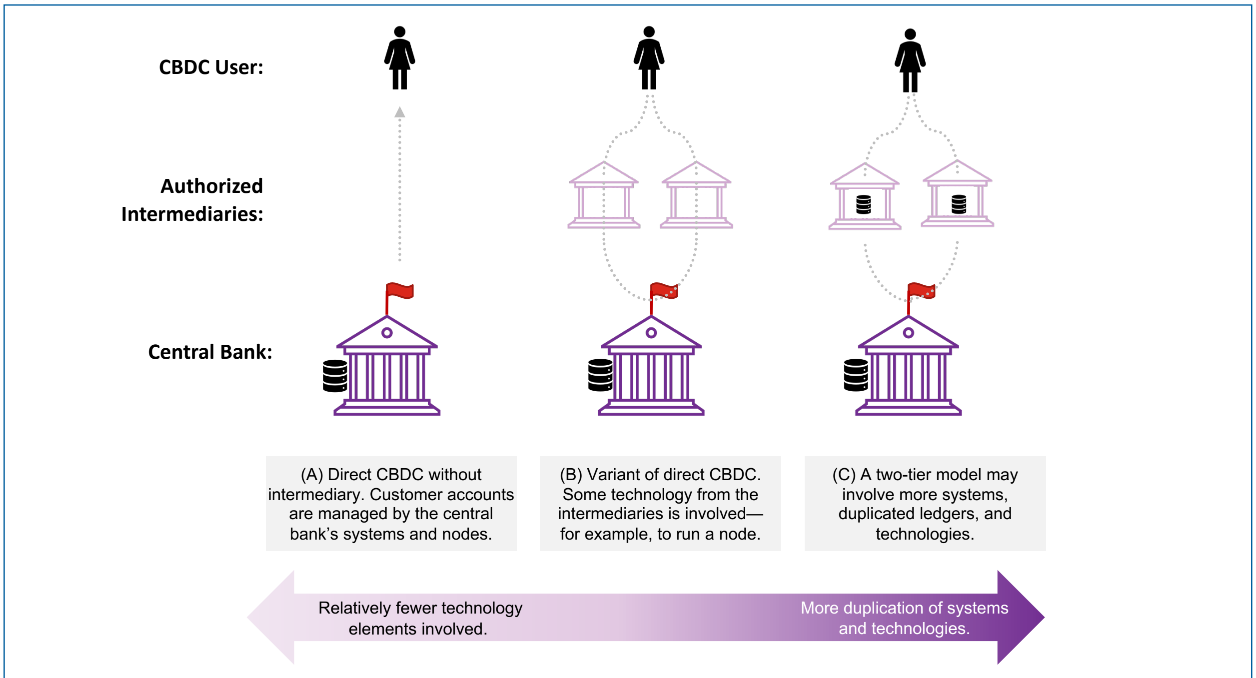
CBDCs may incorporate other forms of user access that could increase energy consumption. Unlike a crypto asset issuer, as a public institution, the central bank is expected to enable universal access to the means of payment it issues, which includes ensuring access for households that have limited digital literacy or connectivity. Choices regarding ease of access and offline capabilities for the CBDC may require the inclusion of energy-consuming components, including card networks. For example, the Central Bank of The Bahamas partnered with a credit card company to improve the offline payment capabilities of its recently launched CBDC, including by allowing the CBDC to be loaded onto physical cards. The People's Bank of China has tested different solutions, such as hardware-based digital renminbi (e-CNY) wallets placed inside mobile phones or held as cards that can make payments to another mobile phone wallet in physical proximity without internet access. Any such additions to the physical infrastructure supporting a CBDC will come at an energy cost that can be weighed as part of the trade-offs in CBDC design. In addition to new features, central banks may also attempt to raise the bar on internet and phone service to ensure uninterrupted user payment access, which can raise energy consumption. For instance, during its CBDC pilot phase, the Central Bank of The Bahamas added local redundancies (telecommunication masts) into the main telecommunication system as part of a plan to improve the resilience of the planned offline capabilities (Soderberg and others 2022).

CBDC dissemination architectures can be more complex than those of permissioned DLT crypto assets, which can raise CBDC energy consumption. Two major models are being considered for CBDC dissemination architectures: a one-tier model, whereby the central bank is directly involved in managing the retail payments; and a two-tier model, where authorized payment stakeholders are involved (Figure 2).[30] One-tier architectures are likely to involve fewer intermediaries and therefore fewer duplications of computing resources than two-tier architectures, resulting in lower energy consumption.[31]

[30] For instance, China has opted for a two-tier model, as discussed in the CBDC White Paper issued by its central bank, as has Nigeria in its recently launched eNaira. Some countries are considering a hybrid model whereby they maintain the possibility to have a direct access to the customer, for example, in case of an intermediary's failure.

[31] The argument that a one-tier model is generally more energy efficient than a two-tier model is by no means a suggestion that a central bank should make a design decision on this argument alone.

Figure 2. CBDC Dissemination Architectures



Source: Authors, adapted from Auer and Bohme (2021) and Soderberg and others (2022).

Compared to crypto assets, CBDCs may be a closer substitute to cash and, depending on CBDC design, this may entail environmental benefits. Several central bank initiatives refer to (retail) CBDCs as a form of digital cash. First, a CBDC is a central bank liability, like cash, and is therefore backed by sovereign credibility. Second, like cash, CBDCs are expected to be issued as legal tender (Bossu and others 2020). Third, CBDCs are generally designed with universal public access in mind, which also resembles cash. CBDCs may therefore be closer substitutes for cash than crypto assets.[32] Some CBDC initiatives specifically target a substitution from cash to CBDCs. For example, one of the reasons that the Central Bank of Uruguay performed a CBDC pilot was to explore a reduction in the costs associated with the use of physical cash. Bergara and Ponce (2018) estimate that these costs amount to 0.6 percent of Uruguay's GDP.[33] The costs associated with physical cash usage, production, and disposal are higher if the environmental impact is considered. This paper does not suggest that a reduction in the use of physical cash should be a policy goal, as cash comes with a variety of social costs and benefits (McAndrews 2020; Rogoff 2017). However, environmental concerns could be included as one of the factors. Furthermore, the extent to which a CBDC could bring about environmental benefits compared to cash will depend on the design specifications discussed previously.

Overall, the environmental impact of CBDCs depends on various design parameters on which the coming years will bring greater clarity. As CBDCs emerge from their infancy, it will become clearer what added facets are common across countries, how these may affect the carbon footprint of this new form of

[32] One counterargument is that in CBDC initiatives currently under way, CBDCs offer little anonymity, particularly toward the central bank, whereas some crypto assets can offer a degree of anonymity, depending on their design and the manner in which they are traded (Goldfeder and others 2018). Because cash is an anonymous means of payment, crypto assets may resemble cash more than CBDC does in this specific respect.

[33] The costs included the production of notes and coins, the transportation and security incurred by banks and retailers, and the costs incurred by consumers in terms of fees paid and other opportunity costs such as interest, time expended withdrawing cash from automated teller machines (ATMs), and the risks of loss and theft.

digital money, and to what extent central banks can design these facets with environmental aims in mind. Central banks may promote carbon-neutral CBDC transactions and may study how large companies are aiming for carbon-neutral operations by offsetting carbon footprint or even by taking CO_2 out of the atmosphere.[34] Programmability features of digital currencies (for example, smart contracts) could support precise policies such as incentivization of climate-friendly behaviors by users and environmental impact accounting.

[34] Although carbon offsetting is now common practice for large groups, notable initiatives promote a carbon-removal strategy.

V. Conclusion

The evolution of payment systems can be probed from the perspective of climate targets. The payment system is undergoing a rapid transformation. This is happening at a time when global targets to rein in climate change are becoming a more central focus for policymakers. It is therefore natural to ask whether the change in the payment system can contribute to these climate goals and whether policy has a role to play in guiding future payment systems toward such a contribution. This paper develops some of the groundwork toward such policy discussions concerning one major trend in the payment system: the growing use of digital currencies. Several possible policy lines emerge from this work.

First, if the transformation of the payment system is to lead to reduced energy usage, then this transformation should not rely on PoW-based DLT applications. In particular, Bitcoin, the best known application of this type, is estimated to consume much energy (about 144 TWh) per year. Although scalability solutions reduce the energy cost per transaction, they do not reduce the overall energy spending.

Second, non-PoW permissioned crypto assets have an edge in terms of energy use over other DLT-based crypto assets and can reduce energy consumption relative to the existing payment system. The advantage of non-PoW permissioned crypto assets compared to other crypto assets, in terms of energy consumption, emanates both from a reliance on more energy-efficient consensus mechanisms and the enhanced ability to influence key parameters of the network that comes with permissioned systems, such as the number or location of nodes, or other eligibility criteria. The potential of non-PoW permissioned crypto assets to reduce energy consumption relative to the existing payment system comes about from energy savings on both core processing architectures and user payment means. Novel non-DLT solutions can provide similar benefits.

Third, central banks could design CBDCs with the explicit goal to be environmentally friendly. For example, central banks could select new platforms, hardware, and design options that are expected to have a lower carbon footprint than the central banks' legacy systems. This could be included in contracts with third parties such as cloud service providers. Because CBDC technologies are still emerging, central banks have a window of opportunity to influence the industry by encouraging vendors to compete on the energy impact of their platforms. Other desirable features that central banks could decide to incorporate in CBDCs, such as compliance, higher resilience, or offline capabilities, will have a say in whether this potential positive environmental impact is ultimately achieved.

Fully informed policy decisions will require further research and cooperation to provide data on the environmental impact of payment systems. Full impact assessments require accounting for all the actors and components of payment systems and to evaluate all types of environmental impact. Currently, data for this purpose are relatively scarce, and methodologies are still in the process of standardization. Moreover, payment systems are complex ecosystems with a large range of actors involved. Self-reporting, independent analysis, and academic research should be encouraged to assess existing solutions and new possibilities.

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Annex I: Energy Consumption of the Current Payment System

To substantiate the statement that the existing global payment system uses nonnegligible amounts of energy, this paper separately estimates the global annual energy consumption of cash and of the digital payment system. The estimates for the latter are based on parts of the digital payment system for which data are available.[35]

Estimates for the Digital Payment System Based on Credit and Debit Cards

According to data from the Committee on Payments and Market Infrastructures (CPMI) Redbook Statistics, credit and debit card transactions constituted 74 percent of all cashless transactions in 2019. This Annex focuses on the energy cost of credit and debit cards, both because of the central role these play in digital payments and the availability of data on their energy intensity.

Various factors underlie energy consumption by credit and debit cards. Several credit card companies provide estimates of their energy use related to data. However, most of these companies do not issue their own cards and instead provide the data processing for cards that are issued by banks, meaning that they cannot provide estimates of the user payment side of the energy cost. To account for the user payment cost of credit and debit cards, data is used from one specific card provider that issues and maintains its own cards. This company estimates its total 2019 energy usage from all sources at 0.377 TWh (or about 0.04 kWh per transaction).[36]

Several scaling factors are used to transform this estimate. First, using data from Statista, this company's share of total credit and debit card transactions is calculated as 2 percent. Scaling up its energy usage estimate to all credit and debit card payments implies a multiplication factor of 50. Subsequently, the above estimate is scaled up to the size of the global digital payment system. First, scaling up from card payments to all digital payments implies a multiplication factor of 1.3, based on the CPMI Redbook Statistics. The implicit assumption here is that card payments are comparable in energy use to other digital payments. Empirical evidence against which to judge this assumption is lacking, but since credit and debit card payments constitute almost three-quarters of all digital payments, an error on this assumption would likely not greatly affect the overall estimate. Last, the estimate is made to account for the fact that the CPMI covers countries that make up 62 percent of the world population with a population scaling factor of 1 / 0.62 = 1.6.[37] Putting the pieces together leads to an estimate of 0.377 x 50.2 x 1.3 x 1.6 = 39 TWh.

Estimates for Cash

The energy use of cash relates to a variety of activities, including printing, transport, and ATMs. Various studies exist on the energy consumption of ATMs specifically.[38] However, only one study, Hanegraaf and

35 The file with the underlying calculations is available on request.

36 Other potential sources of energy consumption are the entry and exit points that the card-based transfers have toward the banking system, discussed in Section II. Rybarczyk and others (2021) provide rough estimates for the energy consumption of the entire banking sector around the world. However, payments are only one of the many different services that banks perform and are not separately estimated.

37 It is reasonable to expect that non-CPMI countries have fewer digital transactions per capita than CPMI countries, as the latter include the major advanced economies and large emerging markets, which likely have more digital payments per capita than countries with a lower level of economic development. Hence, assuming an equivalent energy footprint for digital payments in non-CPMI countries is more likely to overestimate rather than underestimate the energy use of digital payments.

38 See, for example, Haripriya and others (2018), Okundamiya and others (2014), and Singh and others (2016).

others (2020), estimates the total environmental impact of cash from all the activities associated with the creation, distribution, and disposal of both banknotes and coins. The estimate of Hanegraaf and others (2020) centers on the Netherlands. They estimate the total annual environmental impact of cash in the Netherlands at 19 million kg CO_2 equivalents. Using this online tool, this estimate is transformed to 0.0815 TWh, for comparability with other estimates, which are all expressed in energy metrics.[39] Next, this estimate is scaled up according to population shares. Extrapolating from the fact that the Netherlands has 0.225 percent of the world population, the estimate for the global energy consumption of cash becomes 36 TWh.

However, this is not the endpoint of the estimate. The reason for this is as follows. The Netherlands' ratio of cash-in-circulation to GDP stands at 8.9 percent, whereas globally this ratio stands at 9.6 percent. Thus, the Netherlands is not far from the average cash-in-circulation to GDP ratio. However, at \$52,304 GDP per capita, the Netherlands is far above the average global GDP per capita of \$10,926. With a ratio of cash-in-circulation to GDP close to the global average and a GDP per capita far above the global average, the implied cash-in-circulation per capita of the Netherlands should be well above the global average. Therefore, using the population share to extrapolate from Dutch cash use to global cash use overestimates the global energy consumption of cash.

A correction factor can be constructed for the fact that the Dutch cash-in-circulation per capita is higher than the global average. Denoting cash-in-circulation by CIC, this correction factor is:

$$\left[\frac{CIC_{World}}{GDP_{World}}\frac{GDP_{World}}{Population_{World}}\right]\Big/\left[\frac{CIC_{NL}}{GDP_{NL}}\frac{GDP_{NL}}{Population_{NL}}\right]$$

Using the numbers reported above this is:

[(0.096)(10,926)]/([(0.089)(52,304)]=0.23

Therefore, the resulting estimate for the energy use of cash around the world is 0.23 x 36 TWh, which equals 8.3 TWh.

Conclusion

Overall, putting together these estimates based on the parts of the payment system on which data on energy use is available, an estimate of 47.3 TWh of annual energy consumption by the global payment system is obtained. This amounts to about 0.2 percent of total global electricity consumption. That is roughly comparable to the annual electricity consumption of a small, advanced economy, like Portugal, or a sizable developing economy, like Bangladesh.

[39] This conversion factor is based on estimates by UK Department for Business, Energy, and Industrial Strategy, which derive from carbon emissions (and carbon equivalent converted methane and nitrous oxide emissions) by UK power stations per kWh generated. These numbers should be fairly representative for the Dutch economy (given similar levels of economic development and service-based economies), on which the Hanegraaf and others (2020) estimates are based.

Annex II: CBDC Initiatives at Developed Stages

Table. CBDC Initiatives

	COUNTRY	INITIATION / EXECUTION	PROJECT	TECHNOLOGY / PROVIDER	TECHNOLOGY	CONSENSUS / VALIDATION
LAUNCHED	**RETAIL**					
	Bahamas	2019	Sand Dollar	NZIA (including IBM and Zynesis)	DLT	N/A
	Nigeria	2021	e-Naira	Bitt Inc.	DLT	N/A
PILOT	**WHOLESALE**					
	Singapore	2016	Ubin	R3 Corda; Hyperledger Fabric; Quorum	DLT	Centralized; zero-knowledge proof
	Canada	2016	Jasper	Phase1: Ethereum (private network); Phase 2: R3 Corda	DLT	Phase 2: Centralized notary node
	South Africa	2017	Khokha	ConsenSys Quorum (Ethereum blockchain)	DLT	Istanbul Byzantine Fault Tolerance
	UAE + Saudi Arabia	2019	Aber	Hyperledger Fabric; IBM	DLT	N/A
	Canada + Singapore	2019	Jasper-Ubin	R3 Corda; Quorum; JPMorgan; Accenture	DLT	Corda: Notary node; Quorum: Raft or Istanbul BFT
	RETAIL					
	Uruguay	2017	e-Peso	Roberto Giori Company; IBM	Non-DLT	-
	China	2020	e-CNY	Feitian Technologies	Hybrid-DLT	-
	Ukraine	2018	e-Hryvnia	Stellar	DLT	Proof of Authority
	ECCU	2021	DCash	Bitt Inc.; Hyperledger Fabric	DLT	N/A
	South Korea	2021	South Korea CBDC	Ground X (Klaytn); ConsenSys Quorum	DLT	N/A
	Ghana	2021	e-Cedi	Giesecke+Devrient (G+D); Filia	Non-DLT	N/A
	Jamaica	2021	Jamaica CBDC	eCurrency Mint Limited; DSC	Non-DLT	-
	Russia	2021	Digital Ruble	N/A	Hybrid-DLT	-
	Bhutan	N/A	Digital Ngultrum	Ripple; XRP Ledger	DLT	Unique Node List (UNL)
OTHERS	**WHOLESALE**					
	France	2020	France CBDC 2	R3 Corda; Ethereum	DLT	Notary node
	Hong Kong + Thailand	2020	Inthanon-Lion-Rock II	ConsenSys; Hyperledger Besu	DLT	Proof of Authority; Istanbul Byzantine Fault Tolerant 2
	RETAIL					
	Ecuador	2014	EDinero	Mobile Money	Non-DLT	-
	Thailand	2020	Project	ConsenSys; Siam Cement; Digital Ventures	N/A	N/A

	COUNTRY	INITIATION / EXECUTION	PROJECT	TECHNOLOGY / PROVIDER	TECHNOLOGY	CONSENSUS / VALIDATION
EXPERIMENT	**WHOLESALE**					
	Japan + Euro Area	2017	Stella phase 1	Hyperledger Fabric	DLT	Practical Byzantine Fault Tolerance (PBFT)
	Japan + Euro Area	2018	Stella phase 2	R3 Corda; Elements; Hyperledger Fabric	DLT	Notary node
	Japan + Euro Area	2019	Stella phase 3	Hyperledger Fabric	DLT & non-DLT	N/A
	France	2020	France CBDC 1	IZNES (SETL)	DLT	Proof of Authority
	France + Tunisia	2020	France & Tunisia CBDC	Prosperus	DLT	N/A
	France + Singapore	2021	France & Singapore CBDC	Quorum; JP Morgan's Onyx	DLT	N/A
	France + Switzerland + BIS	2021	Project Jura	R3 Corda, OCTO Technology, Accenture, Natixis	DLT	Dual notary signing
	RETAIL					
	Euro Area	2020	Digital euro experiment: WS1	TARGET Instant Payment Settlement (TIPS)	Non-DLT	N/A
	Euro Area	2020	Digital euro experiment: WS2	TIPS + DLT	Hybrid-DLT	N/A
	Euro Area	2020	Digital euro experiment WS3	N/A	DLT	N/A
PROOF OF CONCEPT	**WHOLESALE**					
	Hong Kong + Thailand	2019	Inthanon-LionRock I	R3 Corda	DLT	Notary node
	Switzerland + BIS	2020	Helvetia	SIX Group AG; R3 Corda; SIX	DLT	Notary node
	Australia	2020	Project Atom	Perpetual, ConsenSys, King & Wood Mallesons	DLT	Proof of Authority
	BIS + Australia + Malaysia + Singapore + South Africa	2022	Project Dunbar	Corda; Partior; Quorum	DLT	Notary node; Istanbul BFT; Raft

	COUNTRY	INITIATION / EXECUTION	PROJECT	TECHNOLOGY / PROVIDER	TECHNOLOGY	CONSENSUS / VALIDATION
PROOF OF CONCEPT	RETAIL					
	Sweden	2020	e-Krona	R3 Corda; Accenture	DLT	Notary node
	Japan	2021	Digital Yen	N/A	N/A	N/A
	Turkey	2021	Digital Lira	Aselsan; Havelsan; Scientific and TUBITAK	DLT	N/A
	Iran	2021	Digital Rial	N/A	N/A	N/A
	Thailand	2022	Retail CBDC	Giesecke+Devrient (G+D); Filia	N/A	N/A
	Brazil	2022	Digital Real	Multiple	DLT	N/A
	New Zealand	2022	New Zealand CBDC	N/A	N/A	N/A
	Malaysia	2022	E-ringgit	N/A	N/A	N/A
	Kazakhstan	N/A	Digital Tenge	R3 Corda	N/A	N/A

Source: This table was constructed as follows: Initially, cbdctracker.org, kiffmeister.blogspot.com, and internal IMF sources were consulted to collect the set of country cases. Subsequently, additional information was collected from individual country and technology provider sources.[40]

Note: BFT = byzantine fault tolerance; DLT = distributed ledger technology; N/A = not available.

40 Links to these country sources are available on request from the authors.