A blueprint for energy systems in the era of central bank digital currencies

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Abstract

Central bank digital currencies (CBDC), i.e., electronic cash issued by central banks, are currently being developed and tested in several countries, including the European Union, Canada, China, India and Australia, and will likely become widely available for individuals and businesses in the coming years. In this Perspective, we argue that, if well-designed, CBDCs could provide significant opportunities for energy system innovation and net-zero transition, while addressing certain risks associated with digital cash. We propose a blueprint of a future energy system fully integrated with CBDCs, focusing on energy markets, carbon markets, and energy project financing. We show how this integration could increase transparency, reduce costs, trigger bottom-up citizen-driven energy initiatives, facilitate whole-system regulatory oversight, enhance carbon tracking and trading, and support energy project financing, creating a wealth of opportunities for innovation, financial inclusion in energy investment, and energy consumer engagement. We conclude by identifying major sources of risk and policy implications.

Keywords: blockchain; smart contract; energy market; digital currency; central bank;

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1. Introduction

In October 2020, the Bahamas was the first state to introduce a central bank digital currency (CBDC)[1], i.e. electronic cash issued by a central bank to complement physical banknotes. Since then, ten additional countries, including Nigeria, Jamaica, and several Eastern Caribbean states have adopted CBDCs, while 15 other nations are currently running pilot projects[2]. The largest trial is ongoing in China, where the central bank has been testing the digital renminbi in several regions since April 2021. It has already totalled 360 million transactions, worth almost $14 billion[3]. Other countries, such as Canada, India, and Australia are currently developing their CBDC, while the European central bank (ECB) expects to move to the implementation phase of the digital Euro by the end of 2023[4].

CBDCs can be centralised[5] or decentralised[6]. Centralised solutions can achieve greater transaction throughput and easier interoperability[7], while decentralised approaches may offer better resilience (being distributed systems), and if implemented through blockchains, they can leverage the programmability of smart contracts to unlock innovation[8] and facilitate integration within newer contexts like the 'Internet of Things'[9]. For these reasons, this Perspective focuses on blockchain-based CBDCs.

A blockchain is a cryptographically secure distributed ledger that ensures data integrity, system resilience, and payment traceability[10]. Recent technical solutions, such as permissioned blockchains[11], also allow individual privacy and transactional transparency to be balanced. For example, companies may only be allowed to access data related to their own transactions, while regulators could monitor all transactions to improve market oversight and prevent financial crimes. Despite being implemented through blockchains, CBDCs significantly differ from cryptocurrencies such as Bitcoin, as only the former are legal tender[12], i.e. CBDCs are recognised as cash equivalent by law and cannot be refused as a payment instrument. They also differ from stablecoins, i.e. cryptocurrencies *allegedly* pegged by deposits held by private companies, as these may not guarantee convertibility back to banknotes. By contrast, a CBDC is backed by a central bank, which can always ensure one-to-one convertibility back to physical cash (as a central bank can always print physical money if required). The presence of a central bank is, therefore, an essential element that ensures trust in currency creation and its value, as well as convertibility to cash. Finally, CBDCs differ from electronic payment systems, such as credit and debit cards, as these instruments are issued and backed by commercial banks.

Note that a CBDC could exist alongside physical cash and other electronic means of payment, offering additional freedom of choice to end users. However, as we enter the digital era, a CBDC might represent a key step forward in the evolution of currencies. A CBDC is a secure medium that can potentially be used in any digital payment (even in remote areas not served by traditional banking infrastructure, which would help increase inclusiveness)[13]. Compared to physical cash, a CBDC can offer enhanced security features, reducing the risk of counterfeiting and illicit financial activities[14]. It can also provide central banks with additional monetary policy tools, as they would have more direct control over the money supply and would be able to implement innovative monetary policies, such as helicopter drops[15], to stimulate economic activity or control inflation. Embracing blockchain technology for CBDCs would also allow central banks to stay at the forefront of technological innovation in the financial sector, as this would enable new possibilities for digital finance, while maintaining sovereignty over their currency and payment systems, which would also help mitigate the risks associated with the rise of private cryptocurrencies[16,17]. Moreover, as detailed in Section 3, the presence of a CBDC can enable automated and programmable transactions, which could streamline processes such as supply chain finance[18], cross-border trades[19] and contract settlements[20] (including in energy markets[21]).

In this Perspective, we argue that, if well-designed, blockchain-based CBDCs could provide significant opportunities to enhance the functioning of energy systems. We discuss potential benefits and risks, and propose a blueprint for a future energy system fully integrated with a central bank's blockchain, showing how this could create synergies. In detail, we focus on how the existence of a CBDC, supported by a blockchain operated by a central bank, can foster an ecosystem that can improve the functioning of (i) national and local energy markets, (ii) carbon markets, (iii) regulatory oversight, and (iv) energy project financing, creating a wealth of opportunities for innovation, financial inclusion in energy investments, and consumer engagement into energy systems.

2. A review of the concepts of blockchain, smart contracts and layer-two blockchains

The idea of digital cash is not new, and can be traced back to the 80s[22]. However, it was only in 2008 that a breakthrough was achieved, which solved the problem of double spending in decentralised electronic-cash systems. This was achieved by storing all transaction data in blocks, and then cryptographically linking them together, creating a chain of blocks, i.e. a blockchain[23]. This ensures security and data integrity of the whole blockchain. It also implies that once appended, blocks become inherently tamper-proof and immutable.

The next major innovation was creating blockchains capable of fully supporting the execution of programs of arbitrary complexity, termed *smart contracts*[24]. A smart contract is a program that encapsulates an agreement between parties, and the code to self-enforce its terms[10]. This means that once triggered, a smart contract can autonomously execute the agreement's business logic without any intermediary, significantly reducing transaction costs. Smart contracts are stored in the blockchain's blocks, making them inherently tamper-proof.

Blockchains have several important properties, which include: (i) transaction traceability and transparency, while allowing user privacy, thanks to permissioned blockchains; (ii) immutability and security, as transactions cannot be altered once added to a blockchain; (iii) cost-savings, as smart contracts can execute agreements without the need for third parties, such as clearing houses, reducing fees and overheads; and (iv) resilience, as a blockchain network is a decentralised system run by several nodes, each holding the exact copy of the blockchain data, which removes the need of a central database, and ensures the functioning of the overall system even if some nodes malfunction[10].

Thanks to these properties, blockchain-based solutions leveraging smart contracts have been increasingly proposed[25–29], particularly in energy systems[30,31], for example, for peer-to-peer energy trading[32]. Adopting CBDCs can help improve these tools, as a CBDC can provide a secure and stable means of transaction. This would remove the need to rely on cryptocurrencies, such as Bitcoin or Ether (which would require hedging price risk[33]), and private stablecoins that could expose users to liquidity and credit risks[34].

However, current blockchain technologies have at least two major issues. The first is high energy consumption, which can lead to high carbon emissions. It has been estimated that Bitcoin emissions are comparable to those of Jordan and Sri Lanka[35]. However, this issue can be partially addressed by adopting less energy intense algorithms. For example, the Ethereum network reduced its power consumption by 99.95% (from 5.13 GW to 2.62 MW[36]) by switching from proof-of-work to proof-of-stake consensus method in September 2022[37]. Moreover, recently proposed techniques can further help decrease energy consumption and improve computation speed, for example through "*sharding*", where network nodes are split into subsets ("shards"), and only one of them actually processes a transaction[38–40]. Additional improvements can be obtained by reducing redundancy, e.g., by adopting zero-knowledge proof consensus methods[41]. This shows that while criticisms of the energy consumption of blockchains, such as Bitcoin, are empirically substantiated and widely justified, they should not be generalised to all blockchains, as this inevitably hinders technological advancements and inhibits their uptake[38,42]. The second problem is Scalability, as a CBDC's blockchain should be able to execute hundreds of thousands of transactions per second (TPS). As a comparison, the Bitcoin blockchain can process up to 7 TPS, and Ethereum around 15 TPS[10]. Permissioned blockchains, such as Hyperledger Fabric, can reach 2,000 TPS[43], which however is still well below the 300,000 TPS that are considered required, for example, by China's central bank[44]. This may also worsen the energy consumption problem, suggesting that even more efficient algorithms are required[45]. One of the possible approaches to solve the scalability problem is the introduction of *layer 2* (L2) blockchains[46]. An L2 can be regarded as a complementary blockchain that extends the original one, referred to as layer 1 (L1). An L2 can gather and execute transactions autonomously (therefore offloading a significant part of the computation burden of the original L1 blockchain[47]), and then write inputs and results back to L1. Once data and results are added to the L1 blockchain, they acquire its properties, including security and transparency. Moreover, as both data and results are returned, these can be easily verified if required. L2 blockchains are effective tools to take the computation burden away from the L1, which in turn becomes less congested, making the overall architecture more scalable. We will leverage this hierarchical structure to design an L2 blockchain-based energy system, fully integrated with a central bank's L1 blockchain created to issue a digital currency. Recently, reference [48] outlined a potential structure for a CBDC based on a lower-level core infrastructure operated by the central bank, an intermediary operational layer and a final end-user layer for retail operations, without however providing details on potential implementations or connections with the energy system. Similarly, both works in [49,50] proposed a high-level implantation of a CBDC based on a two-layer framework, without however discussing the potential extension to energy systems.

3. A blueprint for a future energy system fully integrated with central bank digital currencies

Here, we compare the ecosystem (including national and local electricity markets, carbon markets, regulatory oversight, and energy project financing) and the functioning of energy systems under three different paradigms: (i) current state without CBDCs; (ii) introducing CBDCs without further changes; and (iii) an L2 blockchain-based energy system fully integrated with a CBDC's L1 blockchain.

3.1. An example of the current energy system structure

Figure 1 shows an example of the current energy system structure, where CBDCs are not yet present, with a focus on energy markets, carbon markets, and investments. Energy markets include wholesale (where the bulk of energy is traded), and balancing mechanisms, whose purpose is to offset demand and supply imbalances near to real-time. Other markets may also be present, such as forward markets for long-term trading and hedging, auctions to provide capacity and ancillary services, as well as over-the-counter bilateral contracts struck outside regulated exchanges. The set of participants that can directly access these markets is often limited to retailers' suppliers, large consumers (e.g. smelters), and power plants. Small users (e.g. households and small businesses) are excluded due to their limited size, and can only participate if a third party, commonly referred to as aggregator[51], collects and aggregates their bids. However, aggregators are for-profit companies, which means that they do not necessarily pursue the same interests of small users. Cooperation between people at the local level can be achieved e.g. through the recently introduced citizen energy communities[52], even though their adoption is not yet widespread due to barriers such as transaction costs[53], and lack of trust and transparency[54]. Generation investments are performed mainly by large investors, while small-user coordination and participation in energy investments and trials, while successful in some areas of Canada, the US, the UK, Denmark and Germany[55], is far from being the dominant investment paradigm. The next key component is represented by carbon markets, also referred to as emission trading systems (ETS). ETS can be mandatory, as the European Union's cap-and-trade scheme, or voluntary, as in the majority of the USA[56]. ETS allow businesses to trade (i) carbon credits (also termed carbon allowances), which give them the right to emit carbon dioxide; and (ii) carbon offsets, i.e. certified emission avoidance or reduction, resulting from activities such as investments in renewable energy projects, improving energy efficiency, reforestation, and carbon capture and sequestration[57]. Finally, all financial transactions are backed

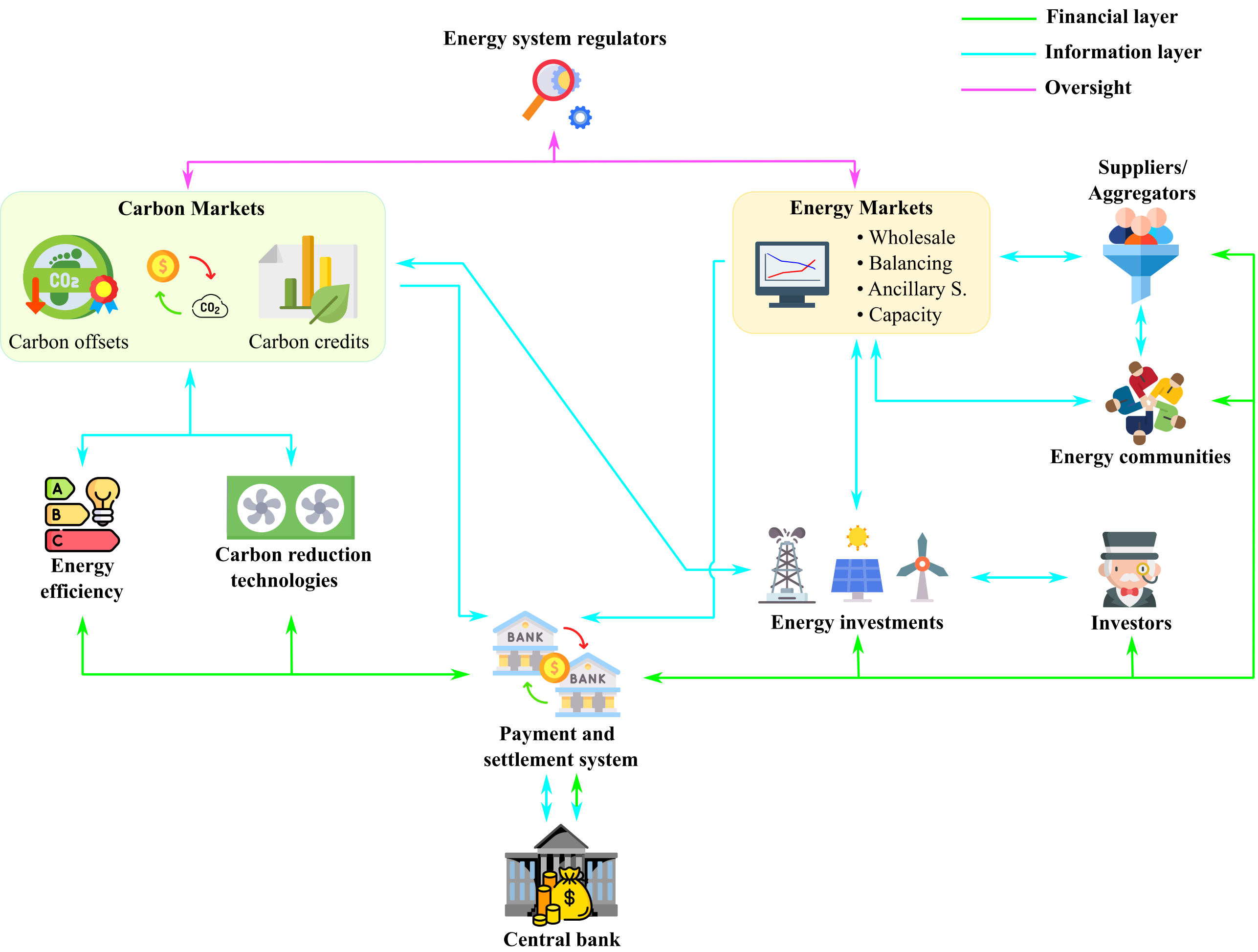

Figure 1. A high-level architectural schematic of current liberalised energy systems where CBDCs are not yet present.

by the payment and settlement system, which is a network of institutions (including central banks) and arrangements required for transferring funds and assets, and ensuring their safekeeping[58].

3.2. An energy system after the introduction of CBDCs

Figure 2 outlines an example of an energy system after the introduction of CBDCs, where transactions and payments are settled through the central bank's blockchain. Here, we assume that the usage of blockchains does not spread to the whole energy ecosystem. This may represent a transitional phase, for example, soon after the introduction of a CBDC, which could be followed by a period where blockchain-based technologies permeate the wider energy system, or may represent the final state with no further major changes (e.g. due to regulatory restrictions). Even without wider changes, this state can offer benefits compared to the existing one, for (at least) three reasons. First, current payment and settlement systems are *centralised*, which means that critical failures can severely compromise their functioning. For example, in October 2020, the ECB's architecture used to settle transactions in all the euro area was subject to a severe disruption due to a technical malfunction, leaving banks unable to process payments and securities trades for almost 11 hours[59]. Similarly, in 2014 the payment system of the Bank of England suffered a 9-hour outage[60]. Adopting blockchain technologies can increase the resilience of these systems, as a blockchain is a cryptographically-secure *distributed* ledger, where each node holds an exact copy of the data. This means that even if some nodes malfunction, the overall architecture will continue to work. Second, in 2020, the ECB printed more than 5.5 billion banknotes and the US Federal Reserve almost 9 billion[44], which then must be physically transported to commercial banks, and stored in ATMs that run 24/7. This process has a significant carbon footprint[61],

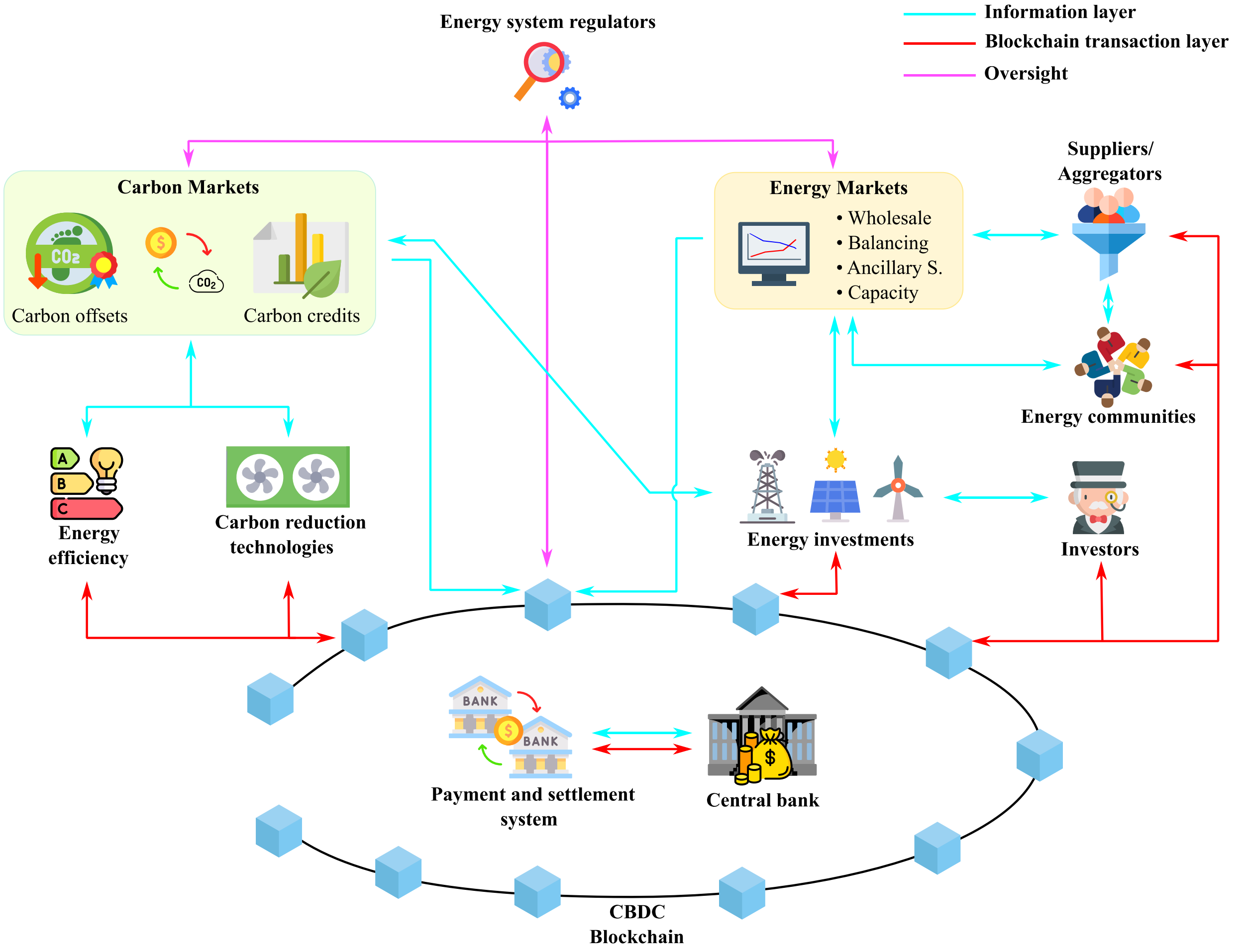

Figure 2. The figure depicts an example of an energy system after the introduction of CBDCs. Here, we assume that blockchain technologies are not adopted by other system components.

which could be reduced by adopting CBDCs supported by non-energy-intense blockchain technologies[62]. Finally, creating a payment system that runs on blockchains can help reduce transaction fees and facilitate financial inclusion, giving more people access to banking services[63]. This can facilitate their engagement in energy systems and help identify disadvantaged groups, such as those living in energy poverty.

3.3. The proposed blockchain-based energy system fully integrated with CBDCs

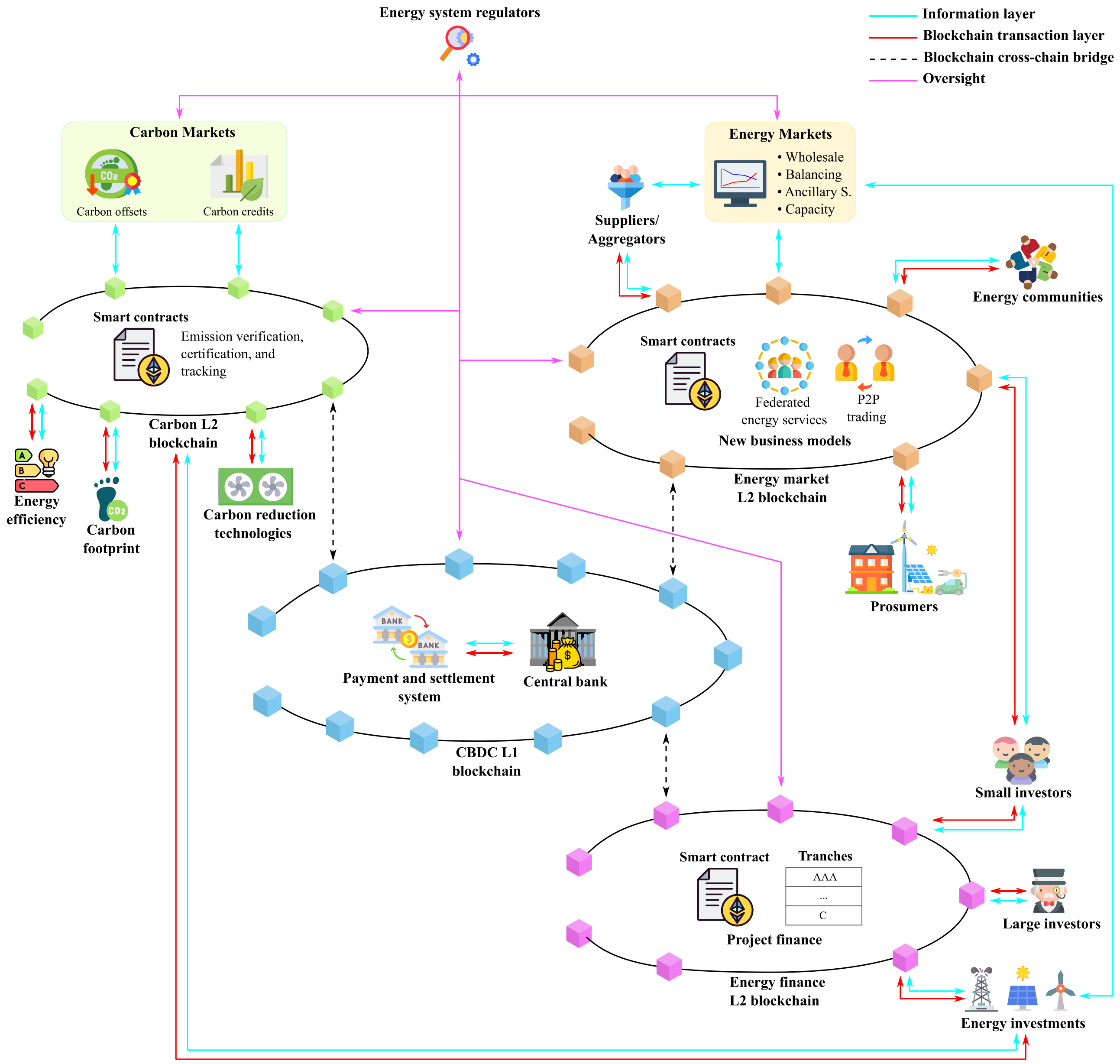

Figure 3. The figure outlines the structure of the proposed energy system, where L2 blockchain technologies permeate all components of the system, and are fully integrated with the central bank's L1 blockchain that supports the CBDC.

The previous section highlighted some of the potential benefits of introducing CBDCs. However, we argue that significantly more value could be unlocked from the energy system if: (i) blockchain technologies would diffuse to all its components; and (ii) these blockchains could be connected to a (lower-level) central bank's blockchain that supports the CBDC. The presence of a central bank is an essential component, and one of the keystones of the proposed architecture. It represents the authoritative and trustworthy institution that provides the foundation layer supporting the overall structure, and that can always ensure the one-to-one convertibility between the digital cash of the energy system transactions and physical banknotes, which cannot be guaranteed by private institutions or commercial banks issuing stablecoins.

The proposed blockchain-based energy system, fully integrated with CBDCs, is outlined in Figure 3. We leverage the L2-L1 concept to propose a hierarchical structure, where (upper-lever) L2 blockchains are used to operate the energy market, carbon market, and energy finance layers. These return transaction data (including inputs and results to make them verifiable) to L1 for settlement and payment, where the L1 represents the (lower-level) central bank's blockchain that manages the CBDC. This architecture ensures scalability, freedom to innovate, and independence of each component, while leveraging the central bank's blockchain that provides: (i) the stable currency; (ii) the trustworthy and resilient base layer; (iii) transparent and secure payment and settlement procedures with no intermediaries, reducing fees and overheads; and (iv) the capability of verifying L2 transactions if required. A key enabler of the proposed structure is the increasing availability of blockchain-enabled internet of things devices[64], also termed "*blockchain of things*"[65]. They are appliances, such as carbon emission sensors and smart meters, connected over the internet that can directly interact with blockchains.

Box 1 – An example of on-demand provision of energy flexibility services with CBDCs

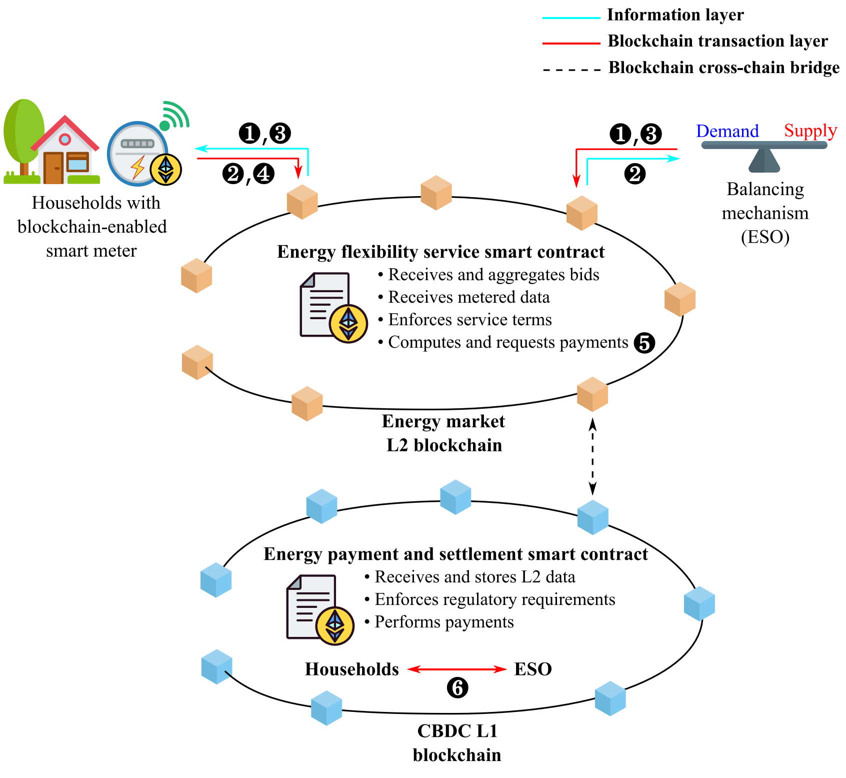

Figure 4. An example of on-demand provision of energy flexibility services with CBDCs.

Figure 4 shows an example of the functioning of the proposed architecture, focusing on the provision of energy flexibility services[21,66,67]. The numbers (from 1 to 6) depicted in the figure indicate the order in which the steps are performed. We assume that flexibility resources are provided by households (e.g. by reducing their electricity consumption), and that they are equipped with blockchain-enabled smart meters (i.e. capable of communicating with blockchains over the internet). An electricity system operator (ESO) can request flexibility resources on demand by interacting with a smart contract that resides in the L2 blockchain (step 1), which in turn makes the request available to all blockchain users. In response (step 2), households submit their bids to the smart contract (which can e.g. aggregate them if these are too small to participate in national-scale markets). The ESO can directly observe all available bids thanks to the transparency offered by blockchains. At gate closure (step 3), the ESO communicates the bids' acceptance to the smart contract, which broadcasts this information to the households. At delivery time (step 4), the smart meters transmit the actual energy utilisation to the smart contract, which (step 5) automatically enforces the service agreement's terms (such as penalties for under-delivery) to determine the net payment. Finally (step 6), the payments are settled by the L1 using the CBDC. No third parties are involved in this process, removing fees and overheads, and regulators can oversee each step thanks to the transparency offered by blockchains.

The proposed architecture could help address some of the current challenges in energy systems and unlock value in several ways. For example, energy markets can substantially benefit from small users' engagement, as they could provide valuable services such as flexibility[68,69]. However, barriers to engagement (particularly to create local energy initiatives) include a lack of trust and transparency, and high transaction costs[54]. An L2 blockchain could help address these problems. For example, a smart contract could aggregate bids from users too small to participate in national-scale markets, replacing for-profit aggregators, and increasing the value and liquidity for spare power capacity[70] (see Box 1). This may also encourage consumers' participation in peer-to-peer energy projects[71] and citizen-led energy communities[72]. Citizens could be directly involved in decision-making processes leveraging smart contracts for voting[73]. This would enable the creation of a community-driven bottom-up energy system that could lead to the co-creation of value and more energy-just platforms[74], increasing trust, project acceptance, and fostering further investments[75]. These systems could be self-operated thanks to smart contracts, which would reduce costs and avoid reliance on third parties. All financial transactions (e.g. in citizen-led energy communities) would be settled by the central bank's L1 blockchain using the CBDC, increasing trust, security, and transparency. Regulators could leverage transparency and traceability to easily access data at each transaction stage and for each energy system component, enabling whole-system oversight.

Box 2 – An example of a voluntary market for carbon offsets with CBDCs

Figure 5 outlines an example of a voluntary market for carbon offsets that leverages smart contracts and CBDCs. The numbers depicted in the figure indicate the order in which the steps are performed. We assume the presence of a carbon capture and storage (CCS) facility equipped with a tamper-proof blockchain-enabled emission sensor. This device could measure the actual carbon captured and stored, and send this data to a smart contract in the L2 carbon blockchain (step 1). A fossil-fuel generator could transmit to the same smart contract its bids to buy carbon offsets (step 2). Bid and offer proposals, and any relevant information (e.g. type of technology, location, project name, regulatory authority), would be securely stored and immediately made available to all participants thanks to the immutability and transparency offered by the L2 blockchain (step 3). The smart contract would automatically match the proposals (step 4), and their payments would be settled by the L1 blockchain using the CBDC (Step 5). Notice that the L1 blockchain can store L2 data, which could include the carbon permit balance of each participant, and L1 blockchains could be linked together, creating a secure, authoritative and trustworthy international network of reliable data that might help avoid double counting.

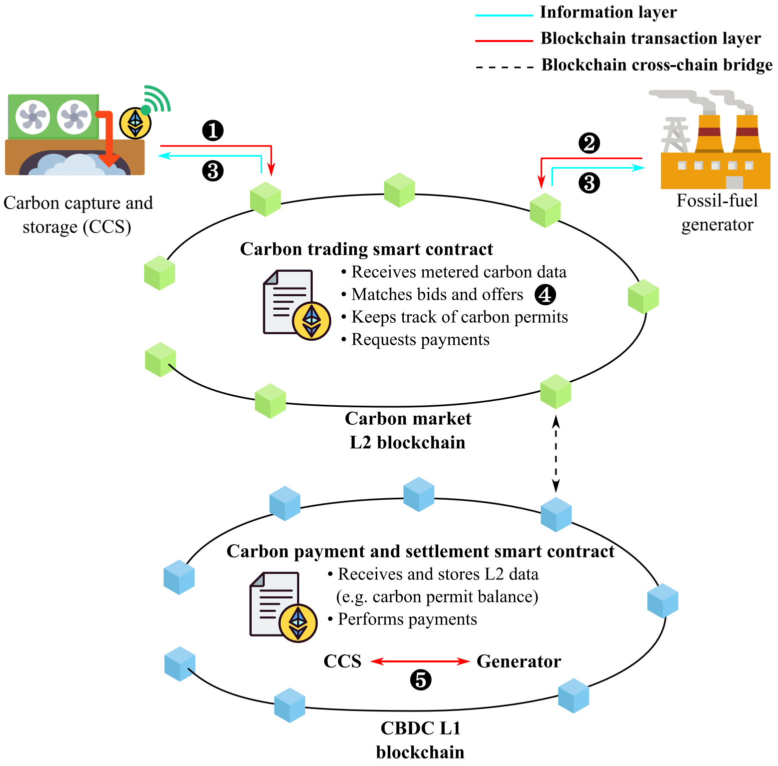

Figure 5. An example of a voluntary market for carbon offsets with CBDCs.

Carbon markets could also benefit from the proposed architecture. Open issues in carbon trading which could be addressed include[76,77]: (i) improving transparency and traceability in voluntary markets; (ii) reducing transaction costs and streamlining multiparty processes; (iii) avoiding double counting; and (iv) linking different markets. An L2 blockchain could ensure traceability and transparency in these systems, and smart contracts could help reduce transaction costs and facilitate the exchange of carbon permits between different markets, whose payments would then be settled and recorded by the central bank's L1 blockchain, helping to avoid double counting (see Box 2). Existing blockchain-based solutions for carbon trading[78] could be linked to the same L1 blockchain to achieve interoperability.

In terms of energy investments, reduced transaction costs, full transparency, and the programmability offered by blockchain technologies and smart contracts could help foster the financial inclusion of small investors in large-scale energy projects. For example, a smart contract could embed the business logic of project finance tools to help pool investors in community-based trust funds[79], or create special purpose vehicles (SPV)[80] to issue and manage asset-backed tranches differentiated by risk profiles, reducing fees and overheads. Small investors could directly invest in these instruments to fund, e.g., renewable energy projects and community energy initiatives[81] (see Box 3). The ECB currently obliges SPV originators to disclose data on a quarterly basis[82]. A blockchain-based system would allow participants to have real-time and simultaneous access to all money flows, removing delays and information asymmetries, and significantly improving transparency, which in turn would help reduce projects' financing costs[83].

Box 3 – An example of blockchain-based energy project financing with CBDCs

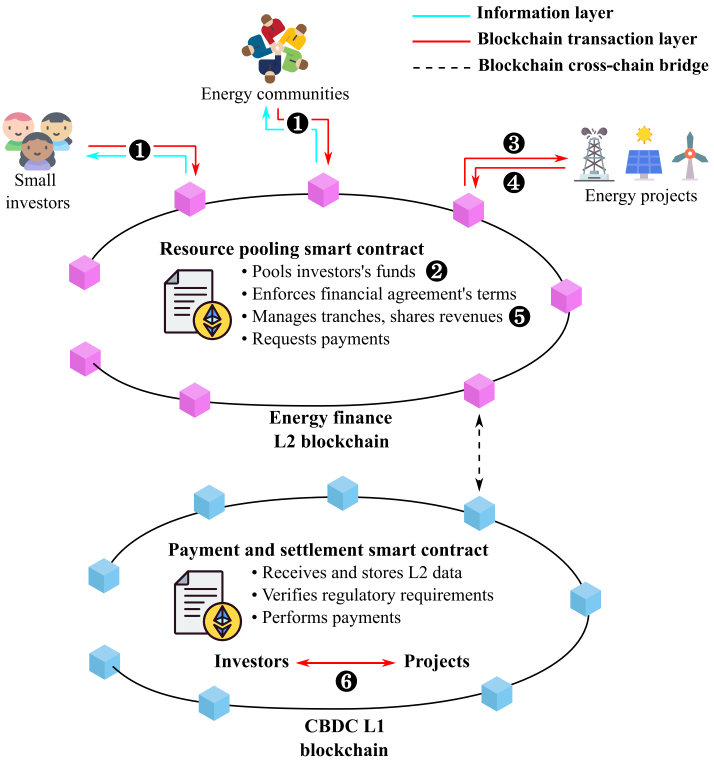

Figure 6. An example of energy project financing with CBDCs.

One of the factors that triggered the financial crisis in 2008 was the information failure caused by a lack of transparency[84]. The lack of transparency and high transaction costs are also key barriers to user engagement in community energy project financing[54]. Figure 6 outlines a blockchain-based energy project financing model that leverages smart contracts to help address these problems. It also relies on a CBDC to settle payments, avoiding financial risks associated with private stablecoins[34]. In this example, small investors and citizen energy communities could directly interact with a smart contract to gather information on projects and offer funds (step 1). The smart contract could autonomously pool the received resources (step 2), which could be used to fund large-scale energy projects and community energy initiatives (step 3). Revenues from these investments would be collected by the smart contract (step 4), which would share them among the investors according to the financial agreement's terms (step 5), whose actual payments would be settled by using the CBDC (step 6). This architecture ensures full transparency and can significantly reduce reliance on third parties, decreasing fees and overheads.

4. Risks and policy implications

The proposed framework can stimulate innovation but also carries significant risks. First, blockchain transparency and traceability can give governments access to all transaction data and related personal information, with potentially no limit on the level of control they could exert on people[63]. Even if robust legal protections are put in place, without technical mechanisms which limit government data gathering and/or access there is a major risk due to the potential for misuse and cybersecurity breaches[85]. In addition, data is immutable once written in a blockchain, which makes it hard to exercise the "right to be forgotten"[86,87]. Second, even if blockchain technologies are transparent and offer innovative instruments such as smart contracts, in practice the level of sophistication required to actually understand and safely engage with them could be a barrier[88], and could expose consumers to unintended consequences including financial losses[89]. Third, the complexity of blockchain-based systems may unintentionally lead to poor designs (particularly at the early stages), for example, if single points of failure[90] are introduced. This would significantly reduce the resilience offered by decentralised systems such as blockchains, and might cause cascading system failures. Fourth, private companies may seize the opportunity to develop their own digital currencies, particularly in the case of central banks' delay. However, even if regulated by governments[91], private stablecoins might still bear liquidity and credit risks compared to CBDCs, leading to a more fragmented and fragile monetary system[92]. Fifth, smart contracts can be used to create autonomous corporations that resides in the blockchain ledger, termed decentralised autonomous organisations (DAO). These corporations are self-governed by terms coded in their smart contracts[93], and may have legal status[94]. This could increase the risk of service disruption and instability, e.g. in case of software error or security vulnerability[95], which may become systemic if these organisations become large and interconnected. Moreover, handling disputes and litigations with such entities could be problematic[96]. Sixth, the blockchain itself is not capable of observing anything in the real world. The necessity for blockchain-of-things devices to provide this information inevitably creates new potential points of failure, and can reintroduce the need for a trusted intermediary to verify the accuracy of the information put on the blockchain. Seventh, implementing and maintaining a CBDC system can pose significant operational challenges for central banks due to the need to develop a robust and scalable infrastructure, manage the transition from cash-based to digital transactions and ensure that the system is not vulnerable to cyberattacks[97]. These potential risks suggest that the proposed blockchain-based ecosystem requires, as a precondition, the development of a comprehensive legal and regulatory framework, reflected in the technical implementation of the CBDC, that must guarantee protections, including: (i) individual privacy, with limits on the level of monitoring and control that governments can exert, and granting appropriate instruments and power to privacy and data protection ombudsmen; (ii) the separation between user funds and those of DAOs and companies running blockchain-based services, such as exchange markets[98]; and (iii) consumer protection mechanisms to safeguard customers and investors and inform them of risks. Moreover, a specific *smart contract regulator* could be introduced (i) to establish a standard set of principles, minimum requirements, and rules for the functioning and development of smart contracts; (ii) to act as the reference body for other regulators and policymakers; and (iii) to exert an overarching oversight on the overall blockchain system[99].

5. Conclusion

Several major economies, including the European Union, Canada, Australia, India, and China are currently developing or testing their CBDCs. This means that the introduction of blockchain-based digital cash backed by central banks may become a widespread reality in the coming years. If these technologies will diffuse to the whole energy system, and if well-designed, they may help unlock significant value from these systems, enhancing their functioning, and creating significant opportunities for innovation. For example, they can help trigger bottom-up citizen-driven energy initiatives at the local level, increase transparency, and reduce transaction costs, while facilitating a whole-system regulatory oversight. Advanced carbon emission tracking and trading schemes could be developed leveraging smart contracts and blockchain-of-things, which could contribute to increasing transparency, traceability, functionality and interoperability in carbon markets. Similarly, smart contracts could embed novel business logic to enhance and develop new project finance tools, helping foster the financial inclusion of small investors currently excluded from large-scale energy investments.

However, if ill-designed, these technologies could lead to service disruption, financial instability and erosion of civil rights, ultimately triggering people's distrust, and wasting an opportunity for innovation. Some preconditions to help avoid this adverse scenario include the development of a comprehensive regulatory framework to unlock the potential value of blockchain technologies safely, and thorough research to investigate and prevent unintended consequences.

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CRediT authorship contribution statement

Iacopo Savelli: Conceptualization; Methodology; Data curation; Formal analysis; Software; Writing - Original Draft. **Cameron Hepburn**: Conceptualization; Writing - Review & Editing. **Thomas Morstyn**: Conceptualization; Methodology; Writing - Review & Editing; Supervision; Project administration; Funding acquisition.

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