The Future of Payments in a DLT-Based European Economy: A Roadmap

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1 Introduction

Distributed ledger technology (DLT) has the potential to address long-standing industrial challenges, remove frictions, build trust, and unlock new value across businesses and industries. It enables decentralization, the immutability of data, transparency, and the automation of business processes. Thereby, it creates a multitude of use cases ranging from energy and manufacturing to mobility and logistics. However, a digitized economy based on DLT can flourish only if it does not merely enable the exchange of assets, goods, and services but also the exchange of money. In other words, there is a need for a payment solution that is compatible with DLT-based decentralized networks and enables transactions denominated in euro. This is particulary relevant in the currently evolving geopolitical environment. Digital payment solutions constitute an important strategic building block in Europe's quest for digital competitiveness and strategic autonomy (Anghel et al., 2020). Various European institutions have increased their efforts to modernize the payment infrastructures in Europe, including the Digital Finance Package from the European Commission (European Commission, 2020) and the inquiry into a digital euro by the European Central Bank (European Central Bank, 2020). Against the background of these developments, we aim to answer the following research questions: What will the future

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of payments in a DLT-based European economy look like? What are the most suitable euro-based payment systems to facilitate the execution of and integration with DLT-based smart contracts? When will these payment systems be operational?

We answer these questions by comparing account- and token-based solutions for the (digital) euro. In our analysis, we consider both the public sector and the private sector as potential issuers of the digital euro. In particular, we analyze possible designs of a digital payment system that enables the transfer of money triggered by DLT-based decentralized business logics, such as smart contracts. These payment systems include solutions based on existing infrastructures, such as bank accounts, as well as novel DLT-based payment rails, such as e-money tokens, synthetic central bank digital currencies (sCBDCs) or a central bank digital currency (CBDC). Our analysis indicates that there will be no single payment solution for a DLT-based European economy. Rather, we expect a broad array of payment systems for multiple use cases to be launched at different points in time. It is unfeasible to expect that there will be a single suitable solution for a wide range of emerging use cases. It is also unlikely that one solution applicable to many use cases will be launched in the short term. Therefore, we propose a roadmap toward a digital euro and the future of payments in a DLT-based European economy that entails a step-by-step timeline of incremental infrastructure solutions.

Several economic and technological trends foster the need for an upgrade of the existing payment system. The ultimate goal is to integrate DLT-based, decentralized business logics with payment systems to enable the seamless exchange of assets, goods, and services and the programmability of payments. Programmable payments already exist today, for example, in the form of standing orders and direct debits. However, it is burdensome to implement complex logic into these payments, and hence their flexibility is limited. Smart contracts offer flexibility and facilitate the integration of complex business processes with payments. A payment system that enables programmable money flows is an important building block for Industry 4.0, including the Internet of Things (IoT), the machine economy, and tokenized assets.

In the Internet of Things, data and value can be transferred based on machine-to-machine interactions. These interactions create an ecosystem known as the "Economy of Things" in which machines, devices, sensors and other physical assets become economic agents that autonomously enter into binding agreements and conduct payments. The Economy of Things increases the efficiency of existing business models and creates new business opportunities. For instance, machine manufacturers can offer their capital-intense machines on a pay-per-use basis instead of selling them to their customers. Another use case would be electric cars that negotiate the price for recharging with a charging station and automatically execute a payment. The Economy of Things already exists on a small scale today. Industry experts expect the number of connected devices to grow strongly over the coming years (e.g., Lueth, 2018).

Another trend that fosters the use of DLT-based smart contracts is the tokenization of tangible and intangible assets. Tokenization refers to the creation of digital representations of assets and rights on a DLT. It brings about several advantages. First, tokenization increases liquidity and facilitates the fractionalization of assets.

Illiquid assets, such as real estate or art, can be represented by tokens and traded on a secondary market. Additionally, investors can own and trade a small fraction of these assets. Second, tokenization can render non-tradable assets tradable. For instance, students could tokenize their future earnings and sell these tokens to investors in order to finance their studies. Third, tokenization increases efficiency by enabling faster and cheaper transactions and settlements because certain steps of the exchange process are automated, and intermediaries become redundant. The key advantage is that decentralized business logics, such as smart contracts, enable mathematically guaranteed settlement and exchange. Consequently, the speed of execution increases and transaction costs decrease because counterparty risk is substantially reduced.

To analyze and compare potential digital payment solutions for the euro that can be integrated within a DLT-based Industry 4.0, we propose a framework in which we decompose the digital payments value chain into the following three pillars: (1) the contract execution system, (2) the digital payment infrastructure and (3) the monetary unit. The contract execution system is the starting point of the digital payments value chain, where a smart contract triggers a payment. The digital payment infrastructure refers to the payment rails. These payment channels can be both DLT-based and based on conventional payment systems, such as the Single Euro Payments Area (SEPA) or TARGET Instant Payment Settlement (TIPS). The monetary unit refers to the unit of account. It can be fiat- or non-fiat-denominated. In this chapter, we analyze and discuss how a digital payment system has to be designed in order to enable the exchange of money that has been triggered by DLT-based decentralized business logics, such as smart contracts. In particular, we distinguish between account- and token-based digital payment systems and focus on payments that are denominated in euros. Finally, we lay out a timeline of potential market launches for different payment solutions.

Our key findings are as follows: Both account- and token-based infrastructures have advantages and disadvantages. We find that systems relying on the existing account-based banking infrastructure are sufficient for most of the relevant use cases in the short term. Token-based solutions will require more time to be developed and implemented, but they will be more effective and able to address the use cases that remain incompatible with account-based solutions. Nevertheless, the account-based payment system will not cease to exist after token-based payments are enabled. We consider the two systems to be complementary. For the future, we envision an increasingly complex world with the euro running on multiple infrastructures (including DLT) and serving different classes of use cases. Consequently, we argue that there will be no one-size-fits-all payment solution. Neither a euro CBDC nor e-money tokens nor sCBDCs alone will be able to address the diverse needs that arise in an increasingly interconnected and automated world. It is essential to work on different payment solutions in parallel not only because they address different use cases but also because they will be rolled out at different points in time. Private-sector solutions building upon existing account-based infrastructures will enter the market soon. The first token-based solutions will also be issued by the private sector and include e-money tokens and sCBDCs. Depending on the progress with regard to technological and regulatory hurdles, these solutions could enter the market in

2022/2023. We do not expect a CBDC issued by the ECB to be rolled out on a large scale before 2026.

The remainder of this chapter is structured as follows. In Sect. 2, we present design paradigms for a future payment infrastructure. Section 3 illustrates multiple payment solutions in detail, ranging from the euro in bank accounts to e-money tokens, sCBDCs and a CBDC issued by the ECB. Section 4 summarizes the advantages and disadvantages of the different payment solutions and outlines a timeline of their potential launches. Section 5 provides concluding remarks. In the Appendix, we present specific use cases for the digital euro.

2 Design Paradigms for a Future Payment Infrastructure

2.1 Account-Based Versus Token-Based Solutions

Payments can be performed and recorded either in account-based or token-based systems.[1] In this analysis, "account-based" refers to the legacy banking system with underlying bank accounts.[2] Bank accounts are based on double-entry bookkeeping, where a bank deposit represents a liability of the bank and hence a claim of the customer against the bank. To initiate a bank transfer, the transaction sender instructs the bank to update the account balances. For the authorization of a transaction within an account-based system, customer authentication procedures are used to verify the identity of the account holder through different types of credentials, such as a password, a PIN, or biometric data.

Table 1 compares account-based and token-based forms of money across different categories, such as convenience, efficiency, and privacy. For illustrative purposes, bank deposits are used as the most prominent account-based form of money, while cash and crypto assets are used as examples of token-based money.

Token-based forms of money, in contrast, are bearer instruments. The authorization of a transaction involving token-based money does not require the verification of the identity of the transacting party but is instead based solely on verifying the validity of the token itself. The token contains all the information necessary for the recipient of the payment to verify its legitimacy. The most prominent example of a token-based form of money is cash. For transacting cash, the authenticity and

[1] Note that there are also hybrid systems that display features of both account- and token-based systems. We do not consider such hybrid forms in this chapter. We also assume for the purposes of this chapter that digital token-based money is implemented by using DLT. This assumption is in line with current token-based CBDC prototypes, such as the CBDC by the Eastern Caribbean Central Bank (DCash).

[2] We note that the term "account" can also be used as a technical term and can refer to the software architecture of some DLT networks or can be a synonym for a digital "wallet." In such a system, "account-based" software design is used to record ownership of digital instruments on a distributed ledger. In this chapter, we do not consider such a technological perspective.

Table 1 Comparison between account-based and token-based forms of money

Category	Account-based money	Token-based money	
	Bank deposits	Cash	Crypto assets
Convenience of transacting and storing money	High	Moderate	Moderate, increasingly more convenient
Risk of theft or loss	Low	High	Moderate
Interoperability with DLT systems (including tokenized assets)	Moderate	Low	High, if based on same DLT
Peer-to-peer transactions	Not possible	Possible only in person	Possible on a global scale
Payment resilience	Low, only online transactions possible	High, offline transactions possible	Moderate, offline transactions possible to a certain extent
Privacy	Low	High	Moderate, as most crypto assets are pseudonymous
Regulatory embeddedness	High	High	Low, but, increasingly more embedded
Payment efficiency	High for national payments and low for cross-border payments	Low, due to transacting in person	High for large-value payments, low for low-value payments

Source The authors

validity of the banknote itself are the only kinds of identification necessary to conduct a payment. Another example would be crypto assets, such as Bitcoin.

Today, money is mainly transacted via account-based systems, such as in the form of bank transfers, credit cards, or mobile payments, which are linked to an underlying bank account. The popularity of such account-based payments is mainly due to the convenient handling of transactions and the comfortable storage of money. In cases where money is deposited with a regulated entity, such as a bank, the risk of theft and other forms of loss of the deposited money is relatively low as the account provider is responsible for record-keeping and managing the accounts. Therefore, the account provider may be liable if funds are lost, and in such a case the client would get compensated. Furthermore, fungibility and interoperability are typically higher in account-based systems. Fungibility means that assets are interchangeable and indistinguishable from one another. Interoperability refers to the ability of the underlying technologies to communicate with each other in order to enable the seamless exchange of assets. The euro within an account-based system is fungible, and the systems are interoperable because financial intermediaries have agreed on common (technological) standards. This is not automatically the case for token-based versions of the digital euro. Different tokens might be issued by multiple institutions on different technological platforms, leading to non-fungible forms of the digital euro that are not interoperable. Finally, account-based money also brings about advantages from a regulatory perspective because accounts are deeply embedded in existing regulatory frameworks.

Nevertheless, account-based systems have several drawbacks related to privacy, resilience, and efficiency, which token-based systems might address. Table 1 summarizes the advantages and disadvantages of account- and token-based money. Tokens can be transacted peer-to-peer as the identification of the token holder through an intermediary is not required. Importantly, it needs to be ensured that tokens cannot be counterfeited or duplicated. As a revolutionary concept, DLT digitally solves, for the first time, the double-spending problem and enables decentralized digital token-based forms of money. Furthermore, DLT enables tokenization, that is, all kinds of physical assets, goods and rights can be represented by digital tradable tokens. Peer-to-peer transactions with token-based money increase payment efficiency as transaction processing is no longer dependent on intermediaries and can be directly conducted between the two counterparties of a transaction. Moreover, this peer-to-peer characteristic increases payment resilience since payments can also be conducted when an intermediary is not available or acts in a malicious way. Moreover, payment privacy can be higher in token-based systems. In account-based systems, the account provider has access to the transaction data, and payments are assigned to the identifiable account holder. Tokens, in contrast, are not necessarily linked to the identity of the holder.

2.2 Contract Execution, Digital Payment Infrastructure, and Monetary Unit

To provide a structured analytical framework for the debate about payments in a DLT-based European economy, we decompose the digital payments value chain into three pillars: (1) contract execution system, (2) digital payment infrastructure, and (3) monetary unit (see, Fig. 1). The contract execution system concerns the programmability of payments, i.e., DLT-based smart contracts implemented and integrated with business processes. The digital payment infrastructure is the payment rail, i.e., the system facilitating the transfer of money. Finally, the monetary unit is the unit of account transacted on the digital payment infrastructure. Payments can be denominated in euro, US dollar, and other fiat or non-fiat currencies.

Contract Execution System

The contract execution system is the first pillar of the digital payments value chain. It comprises decentralized business logics that automate business processes and trigger payments in a predefined way. Programmable payments already exist in today's

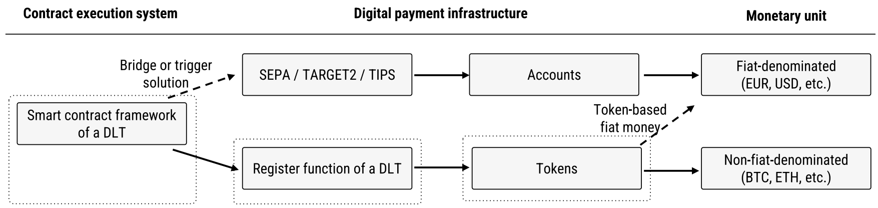

Fig. 1 Digital payments value chain. *Notes* SEPA: Single Euro Payments Area; TARGET2: Trans-European Automated Real-time Gross Settlement Express Transfer System; TIPS: TARGET Instant Payment Settlement; DLT: Distributed Ledger Technology; BTC: Bitcoin; ETH: Ethereum. "Fiat-denominated" is a broad category and includes money issued by the government, which has a status of legal tender and other forms of fiat-denominated money. *Source* The authors

banking system in the form of standing orders and direct debits, but current programming capabilities and system capacity are very limited. DLT networks provide more flexibility and capability, for instance, via smart contracts.[3]

Smart contracts can be applied to execute, control, and document transactions. They can be used to pre-program money flows and automate payments and processes. Payments executed via smart contracts are automatically triggered when predetermined conditions are met. Examples include business processes involved in escrow arrangements, standing orders, interest payments, factoring, leasing, rent deposit accounts, loans, machine-to-machine payments, and exchanging tokenized assets.

In the Economy of Things, machines will become market participants, negotiating prices, and making payments on their own. For instance, an autonomously driving electric car might drive to the next charging station, negotiate a price with the charging station, carry out the charging process, and conduct a payment. The process of negotiating, recharging, and triggering the payment is part of the contract execution system. The payment could be split and transferred directly to all stakeholders as predefined in a smart contract (e.g., 70% to the electricity provider and 10% each to the charging station manufacturer, gas station operator, and car manufacturer).

Digital Payment Infrastructure

The second pillar of the digital payments value chain, the digital payment infrastructure, determines which payment channels are used to process and settle the payments. Within the digital payment infrastructure, we distinguish between the system operator, such as a bank, central bank, or another entity, and the underlying technology, whether DLT or otherwise. The payment infrastructure must be distinguished from the monetary unit, that is, from the unit of account that is ultimately used for the payment. Payments executed in euro are currently supported by existing

[3] We acknowledge the evolving landscape of technological solutions for the deployment of decentralized business logics onto DLT. Business logics can be implemented either directly inside the core DLT layer or as a sandbox smart contract solution. We refer to smart contracts in a broad sense, that is, as computer programs that can implement business logics and automate business processes in a predefined way without reference to any specific technological architecture that may or may not give rise to questions of legal enforceability or risk of undesirable effects of these contracts.

legacy banking systems and traditional bank accounts. In the world of crypto assets, DLT networks such as Bitcoin or Ethereum constitute digital payment infrastructures for payments denominated in non-fiat currencies.

Traditional bank accounts can be used to process payments that have been triggered by DLT-based smart contracts. To this end, they have to rely on a so-called bridge solution, which connects the DLT network (i.e., the DLT-based contract execution system) and the legacy payment system (i.e., bank accounts). Hence, payments are triggered by DLT-based smart contracts, but they are processed via traditional bank accounts. Against this background, the bridge solution is also called a "trigger solution."

In the electric car example, the digital payment infrastructure defines the payment channels used for the settlement of the payment. This infrastructure can be the legacy system, such as SEPA, or DLT-based payment rails. Since bridge solutions are not yet available outside of test environments, payments triggered by a DLT-based contract execution system can be settled only via DLT-based payment channels. However, these channels do not yet allow for transactions denominated in euro. This leads to the third pillar of the digital payments value chain—the monetary unit.

Monetary Unit

The monetary unit refers to the unit of account in which payments are made. It can be denominated in fiat currencies, such as the euro and US dollar, or in non-fiat currencies, such as Bitcoin and Ether. Technically, currencies such as the euro could be processed through multiple different digital payment infrastructures.

3 Euro-Denominated Payment Solutions for DLT-Based Smart Contracts

In this section, we outline how the digital payments value chain could be implemented and linked to DLT-based use cases. First, we consider existing account-based infrastructures and then token-based solutions. All possible solutions are illustrated in Table 2. Use cases are discussed in the Appendix.

3.1 Account-Based Solutions

Euro on Bank Accounts

Definition. The term "bank account" refers to a financial account opened by a customer with a financial institution—usually a bank—that maintains the account on behalf of the customer by recording financial transactions. By depositing money in the account, the customer transfers the money to the bank in exchange for a claim against the bank for the sum deposited. Bank accounts form part of the legacy banking system

Table 2 Four solutions to implement the digital euro

Digital euro	Contract execution system (Pillar 1)	Digital payment infrastructure (Pillar 2)		Monetary unit (Pillar 3)
	Technology	System operator	Technology	
Euro on bank accounts	DLT	Commercial bank	No DLT (account-based)	Euro (commercial bank money)
E-money token (EMT)	DLT	Commercial bank or e-money provider	DLT (token-based)	Euro (e-money)
Synthetic CBDC	DLT	Commercial bank or e-money provider	DLT (token-based)	Euro (tokenized commercial bank money or e-money, but 100% backed by central bank reserves)
CBDC	DLT	ECB	DLT or not DLT (account- or token-based)	Euro (central bank money, legal tender)

Source The authors

governed by well-developed legal and regulatory frameworks. To process payments via the existing banking infrastructure, several systems, processes, and participants are involved, including clearinghouses for settlement and messaging networks for payment instructions.

Application. To process payments triggered by the DLT-based contract execution system, bank accounts need to be connected to a DLT with the help of a bridge solution. Connecting DLT-based contract execution systems with a digital payment infrastructure based on the legacy banking system benefits from the well-established banking infrastructure and legal certainty of existing legal, regulatory, and compliance frameworks. This solution would be the least disruptive as it would be the closest to existing payment solutions. However, the suitability of such a solution for all DLT use cases is less convincing. The DLT-empowered machine economy involves hundreds of millions of machines that would have to be linked to bank accounts and would involve processing a multitude of micropayments across currencies and jurisdictions. This is not feasible via existing banking infrastructures. Furthermore, international payments tend to be slow and costly, particularly in territories outside Europe and without well-established cross-border payment architectures (World Bank, 2018). Despite advancements in modernizing legacy banking infrastructures, there are challenges to providing seamless integration with tokenized assets and rights. Furthermore, when a bridge solution is used, a number of intermediaries would continue to be involved in the payment process. This intermediation causes inefficiencies that can be addressed with token-based solutions.

Regulation. Payments based on existing banking infrastructures are governed by existing legal and regulatory frameworks. Banks and financial institutions are closely regulated, supervised, and bound by regulations designed to mitigate risks. There are policies and regulations in place preventing financial institutions from taking excessive risks and ensuring that adequate protections for customers are in place, such as deposit insurance schemes. Banks have well-developed customer-facing infrastructures with integrated anti-money laundering (AML) and know-your-customer (KYC) compliance procedures and systems adapted to the continuously evolving regulatory landscape.

Technology. Payments triggered by a bridge solution and processed via the legacy banking system are easily scalable within the existing infrastructure. There is no need for costly large-scale investment or disruptive changes to banking operations. Payment processes within the existing banking infrastructures benefit from interoperability within a single country and within the territories with well-developed payment infrastructures (such as in Europe). SWIFT also enables a certain level of worldwide interoperability of payment messaging services. However, the technological disadvantage of this solution is that legacy banking infrastructures do not effectively support micropayments and delivery-versus-payment settlement mechanisms.

The European payment infrastructure has been undergoing major modernization efforts and is well-positioned to cater to the digital economy. A new market infrastructure—TARGET Instant Payment Settlement (TIPS)—was launched by the Eurosystem in November 2018 and is based on a pan-European instant payments scheme called SEPA Instant Credit Transfer. It enables instant round-the-clock pan-European final and irrevocable settlement of payments. TIPS settles euro payments in central bank money and is an extension of the existing TARGET2 system, which is already widely used across Europe. SWIFT has already successfully implemented its messaging service for TIPS and has become one of the network service providers of TIPS.

Time horizon. Connecting a DLT-based contract execution system (or multiple DLT systems) to the existing banking infrastructure could be implemented quickly and efficiently, relying on existing technology. The first bridge solutions entered test mode in 2021 and are expected to enter the market soon.

Costs. DLT-facing interfaces can be implemented relying on the existing IT systems and banking infrastructure, which would remain unaffected. They could also cater to multiple DLT systems and can be implemented in a cost-efficient way.

Dependencies and risks. Using legacy banking infrastructures for payments carries risks. These risks include counterparty risk because commercial banks, financial institutions, and other actors intermediate these payments and process commercial bank money, not central bank money. For cross-border payment transactions, market participants have historically relied on SWIFT's global network for cross-border messaging, which enables financial institutions worldwide to exchange payment instructions in a secure and fully standardized environment. The downside of the SWIFT system is that it does not facilitate the transfer of actual funds and does not provide clearing and settlement services. Transacting banks must process SWIFT payment instructing messages themselves and settle payments through foreign exchange markets, which delays and increases the costs of cross-border payments. Smaller financial institutions without established business relationships with foreign counterparties may not be able to use the SWIFT network. Furthermore, there are controversies and concerns over the monitoring level and access of third parties (such as governmental agencies) to the SWIFT transactional data. For example, SWIFT has been subject to legally binding requests from government authorities to give access to data and is also subject to various regulations. This sometimes results in disconnecting certain sanctioned countries or companies from the network.

Account-Based CBDC

Definition. A retail CBDC is a novel, digital form of central bank money, which would be made available to the general public.[4] Central bank money constitutes a claim against the central bank and hence is risk-free.[5] There are various design solutions for a CBDC, including direct, indirect, and hybrid CBDC distribution models (Auer & Boehme, 2020). In the case of a direct CBDC model, the central bank distributes CBDC units directly to the end user, while in a hybrid CBDC model, the CBDC is distributed via intermediaries. In this section, we focus on a non-remunerated, hybrid retail CBDC, in other words, a CBDC that provides a direct claim on the central bank is non-interest-bearing and is distributed via intermediaries. We do not analyze a direct account-based CBDC, where the central bank distributes CBDC units directly to the end user, as this design option is not considered in current CBDC projects and prototypes (Auer et al., 2020). In the case of an account-based CBDC, the CBDC holder must be identified in order to authorize a CBDC transaction (see Sect. 2.1).

Application. As the primary use case, an account-based CBDC constitutes a general means of payment (European Central Bank, 2020). Depending on its implementation, a CBDC can also be made available globally and could be used for cross-border payments, which could significantly increase cross-border payment efficiency. As an account-based CBDC would—according to current developments—most likely not be implemented on a DLT, the benefits related to micropayments and tokenization would remain marginal.

Regulation. A CBDC would be compliant with all regulatory requirements. However, legal frameworks would have to be adapted, including, for example, resolving KYC, AML, counter-terrorist financing (CFT) compliance, and data management issues, and making a determination on the legal status of the CBDC.

Technology. An account-based CBDC would most likely be implemented based on a conventional, centralized infrastructure that is not DLT-based. As the ECB would

[4] In this chapter, we do not consider wholesale CBDCs, referring to central bank money only accessible by banks. We solely consider payment solutions available to the general public.

[5] In this context, we abstract from inflation risk as this affects all forms of money.

operate (most of) the payment infrastructure, such a CBDC would be interoperable. However, a centralized implementation would carry IT security risks due to a potential single point of failure (Kiff et al., 2020).

Time horizon. A CBDC would be interoperable and would not expose the holder to counterparty risk. While these features are desirable, it would take time to launch such a CBDC. Before a CBDC can be launched, regulatory adjustments have to be made, and the CBDC infrastructure has to be set up and tested. Furthermore, risks related to financial stability have to be addressed (see next paragraph). We estimate that the launch of a CBDC in the euro area is unlikely to take place before 2026.

Cost and risks. If a CBDC replaces (at least partly) cash and bank money as the means of payment, a large number of payments would be conducted in the CBDC. The substantial use of a CBDC would have the following implications. First, it could cause disintermediation of the banking sector since the end-user would rely less on commercial bank money. As a consequence, refinancing costs for banks could increase, thereby potentially disrupting the financial sector (Bindseil, 2020). Second, bank runs on commercial bank money could become more likely as they are easier to carry out with digital CBDCs as compared to physical cash (Sandner et al., 2020). Both disintermediation and a higher likelihood of bank runs might affect financial stability. The actual impact of a CBDC on the financial sector strongly depends on the design of the CBDC and the policy conducted by the ECB (Gross & Schiller, 2021). In a case where the ECB decides to introduce a cap on CBDC holdings (Panetta, 2018) or a tiered remuneration (Bindseil, 2020), the negative effects on the financial sector might only be marginal. Third, a CBDC might change the existing monetary system's character to a full reserve system, whose implications are currently difficult to assess. Fourth, due to the widespread use of CBDCs, the balance sheet of the ECB would grow substantially, implying financial risks for the central bank and—in the end—for taxpayers.

3.2 Token-Based Solutions

As mentioned previously, we assume that token-based solutions are digital bearer instruments based on DLT. Using DLT for the entire payments value chain provides several benefits. First, the use of DLT would enable real-time settlement with other assets or DLT-based currencies (i.e., delivery-vs-payment). Second, DLT would support the tokenization of all kinds of assets in addition to money. Third, by using DLT, trust would be shifted from institutions, such as commercial banks, central banks, and other financial institutions, to technology as executing a transaction would not necessarily require an intermediary. Counterparty risk is, thereby, significantly reduced or altogether removed. This latter aspect is one of the key points advocating for DLT as it is the key driver for more efficient systems. Fourth, business processes could be operated more seamlessly by removing system breaks, and automation can be increased. In the following sections, we discuss token-based solutions for the digital euro. For this purpose, we address e-money tokens, sCBDCs, and a token-based CBDC.

E-money Token (EMT)

Definition. Euro-denominated e-money tokens (EMTs) are a token-based form of the digital euro issued by the private sector. EMTs are defined in the European Commission proposal for a Regulation of the European Parliament and of the Council on Markets in Crypto-assets, and amending Directive (EU) 2019/1937. The EMT category will include different existing forms of DLT-based tokens that reference the euro, such as tokenized e-money and euro stablecoins.

Tokenized e-money is a DLT-based form of e-money as defined in Directive 2009/110/EC (e-money directive [EMD]). It is issued at par value to the euro, and the holders are provided with a claim on the issuer as well as the right to redeem the e-money at par at all times. Issuers of tokenized e-money must be authorized and are subject to the full e-money regulatory regime, including capital, safeguarding, and conduct of business requirements. Tokenized e-money is backed by safeguarded funds received from e-money customers, which must be either segregated or insured and guaranteed.

Stablecoins that reference the euro are an alternative, privately issued and token-based form of the digital euro.[6] Since they may currently fall outside of the regulatory regime of the EMD, they may not provide the holders with the right of redemption or a claim against the issuer. Additionally, they may not necessarily be backed by safe and liquid assets but by risky ones, such as crypto assets. Stablecoins can even be completely unbacked. Since stablecoins will fall under the scope of MiCA, they will have to be compliant with these regulatory requirements, as they will otherwise effectively be prohibited in the EU after MiCA becomes applicable.

Application. EMTs can be used for a wide range of use cases. Since they constitute crypto assets, they are transferable on a global scale and can be seamlessly integrated into DLT-based environments to serve as a means of payment, for example, for the machine economy or tokenized assets and rights. However, for an efficient application of privately issued EMTs, it is crucial that issuers agree on a technological standard to ensure interoperability.

Regulation. Under current EU regulations, DLT-based instruments referencing the euro may fall under a number of different regulatory frameworks, including regulations governing banks, e-money issuers, or investment funds. A number of characteristics determine the applicable regulatory regime, including the existence of the claim against the issuer, a guarantee of redeemability, credit provision, or asset

[6] Since this chapter focuses on DLT-based payment solutions for the euro, we exclusively focus on stablecoins referencing a single fiat currency. Hence, we exclude stablecoins that reference a basket of fiat currencies, crypto assets, or a commodity (index), which will fall into different regulatory categories. Furthermore, we do not consider algorithmic stablecoins.

management function. Some of these instruments may even fall outside the existing regulatory frameworks.

MiCA seeks to provide legal certainty and creates a bespoke regulatory regime for all crypto assets that have as their main purpose to serve as a means of exchange and that refer to a single fiat currency. To avoid regulatory arbitrage between e-money and e-money tokens, MiCA proposes that e-money tokens that are indistinguishable from e-money be subject to two regimes—the new MiCA regulation and the EMD. Accordingly, the issuer of such e-money tokens must be authorized as an e-money or credit institution and comply with the relevant governance and redemption rules. All e-money tokens will have to be issued at par value, and the holders will have to be provided with a claim on the issuer and right of redemption at any moment and at par value. E-money tokens that do not fulfill the regulatory requirements set out in MiCA will not be permitted to be offered to the public nor to be admitted to trading on a trading platform for crypto assets in the EU. So-called significant e-money tokens will be subject to stricter rules and requirements. Through MiCA, Europe has the opportunity to be one of the first jurisdictions to provide legal and regulatory certainty for the issuers as well as end users of privately issued and DLT-based forms of fiat currency.

Technology. EMTs can be issued on any appropriate DLT. Since EMTs are crypto assets, they can be subject to scalability issues.

Time horizon. The EMT category has not yet been implemented because MiCA will only be applicable 18 months after the date of entry into force, which is unlikely before the end of 2022. Nevertheless, the predecessors of EMTs—tokenized e-money and stablecoins—already exist today. Since tokenized e-money already complies with some of the requirements specified in MiCA, there should be a smooth transition into the new regulation. Those euro stablecoins that do not fulfill the requirements under MiCA will not be permitted. Consequently, MiCA will most likely affect the operations of some of the existing stablecoin issuers.

Cost and risks. MiCA and the introduction of EMTs provide a regulatory framework aimed at mitigating financial stability risks. In particular, risks related to stablecoins will be mitigated once MiCA has entered into force. So far, stablecoins have depended on the management of a one-to-one peg between the underlying asset(s) and the specific reference currency. The management of the peg requires substantial assets and introduces counterparty and liquidity risk. It might occur that the obligations to manage the peg are not fulfilled, either due to inaction, insufficient resources on the part of the issuer of the stablecoin, or the illiquidity of the underlying assets. Consequently, stablecoins expose their users to the risk that the peg could break. Currently, given the lack of a uniform regulatory framework applicable to stablecoins, stablecoin issuers are not always subject to obligations to redeem the stablecoin, and end users are not always provided with a claim against the assets of the issuer. MiCA aims to mitigate these risks and provide legal certainty and a uniform regulatory framework for all stablecoins and tokenized e-money. However, even when governed by MiCA, EMTs remain a private form of the digital euro. Consequently, they carry counterparty risk and are not risk-free like a CBDC.

Synthetic CBDC (sCBDC)

Definition. Synthetic CBDCs (sCBDCs) are liabilities issued by private-sector intermediaries and are denominated in the domestic unit of account. They are fully backed by central bank reserves and are redeemable for central bank money at any time (Adrian & Mancini-Griffoli, 2019). sCBDCs are based on a public–private partnership that exploits the comparative advantages of the private and the public sectors. The private sector (i.e., banks or other licensed intermediaries) is responsible for innovating and building intelligent solutions for end users. The responsibilities include technology choice, data management, and regulatory compliance as well as customer onboarding, management, screening, and monitoring (including KYC and AML/CFT). The public sector (i.e., the central bank) focuses on financial stability, regulation and supervision. In other words, the central bank supports innovation within the boundaries of legal and regulatory frameworks.

Application. The use cases of sCBDCs are very similar to those of EMTs. Since sCBDCs are fully backed by central bank reserves, the tokens are fungible. Therefore, different sCBDC tokens issued by different intermediaries are indistinguishable and are always pegged one-to-one to the euro. However, fungibility does not imply that different sCBDC tokens are indistinguishable from a technological perspective. If intermediaries do not agree on a joint technological environment, these tokens would not be interoperable and could not be seamlessly exchanged despite their fungibility.

Regulation. As of today, the regulation of sCBDCs has not been addressed. Issuing sCBDCs through intermediaries, who would be responsible for the entire process—from issuance to distribution to payment system to customer interface—raises regulatory and supervisory issues similar to those of the current banking system. Certain regulatory adjustments will be necessary to deal with appropriate regulatory authorizations, standards, supervision, and liability issues of sCBDCs issuers and other service providers according to their roles and relevant risks. Since sCBDCs are backed by central bank reserves, issuers of sCBDCs require access to the central bank's reserve accounts, which, as of now, requires a banking license. However, so far, even banks have not been allowed to utilize their access to central bank reserves to issue fully backed commercial bank money. It remains to be seen, therefore, whether central banks will allow the issuance of fully backed sCBDC tokens. All participants in a sCBDC ecosystem would need to be subject to the relevant regulatory requirements and standards in order to mitigate risks from their potential operational or financial failure, fraud or cyber risks. Any regulatory framework would need to be innovation-friendly and technology-neutral and would need to ensure resilience, interoperability and minimum standards of consumer protection. Since sCBDCs could effectively be bank-issued stablecoins—albeit backed with central bank reserves—they might also fall into the EMT category and be subject to the regulatory framework provided by MiCA.[7]

Technology. sCBDCs can be issued on any appropriate DLT. Depending on the underlying DLT framework, sCBDCs might be subject to scalability issues similar to those of EMTs.

Time horizon. sCBDCs could be implemented faster than a direct or hybrid CBDC because the agile and innovative private sector plays a larger role. More precisely, the development of a token standard, customer onboarding, compliance with AML and CFT, etc. will all be conducted by the private sector. Fast implementation could be important in light of serious competition from the public (e.g., Chinese CBDC) and private (e.g., Diem, formerly known as Libra) domains. We expect sCBDCs to be operable in 2023.

Cost and risk. The success of sCBDCs depends on the ability of the private sector to agree on common token standards to ensure interoperability. In recent years, several initiatives have shown that coordination among European financial institutions poses challenges. This standardization process might delay or even prevent the introduction of sCBDCs. Furthermore, in the euro area, only banks have access to central bank money. Hence, if the ECB intends to enable other financial institutions (e.g., e-money providers) to offer sCBDCs, it would need to grant these institutions access to central bank accounts and allow the full backing of tokens with central bank reserves in dedicated escrow accounts.

Token-Based Retail CBDC

Definition. A token-based CBDC also constitutes a digital form of central bank money available to the general public. It represents a new form of central bank money—a central bank liability incorporated in a digital token (Bossu et al., 2020). In contrast to an account-based form of money, to authorize a transaction, the validity of the object transacted, that is, the token itself has to be verified. In the case of a token-based CBDC, the transacted object is the CBDC itself.

Application. Similar to an account-based CBDC, a token-based CBDC would constitute a general means of payment, potentially also available for cross-border payments. A token-based CBDC can potentially be used for industrial use cases related to the machine economy and tokenization. However, most of the existing CBDC projects fail to take into account features of programmability. Even more so, they are mostly consumer-focused and give little or no consideration to the needs and challenges of the machine economy and tokenization. Therefore, private-sector solutions might fill the gap and complement a CBDC to exploit the full benefits of programmable payments.

[7] This is subject to any regulations that may be applicable to sCBDCs that are yet to be determined.

Regulation. As in the case of an account-based CBDC, a token-based CBDC would need to be compliant with all regulatory requirements. Existing regulatory frameworks and legal concepts would have to be adapted to fully integrate a token-based CBDC, including determining its status as a legal tender and examining private law issues.

Technology. It is reasonable to assume that a token-based CBDC will be implemented using DLT. This assumption is in line with current token-based retail CBDC prototypes. Even though a CBDC would most likely be interoperable, DLT-related technical challenges remain, including scalability issues for a high volume of transactions and IT security issues.

Time horizon. A token-based CBDC might be introduced in the medium to long run. Similar to the case of an account-based CBDC, the launch of a token-based CBDC is unlikely to take place before 2026. Note that, ultimately, either an account- or token-based CBDC will be introduced. It seems unlikely that both forms will exist in parallel.

Cost and risks. As in the case of an account-based CBDC, the main risks are related to disintermediation of the financial sector, a higher likelihood of digital bank runs, and a larger balance sheet of the central bank.

4 Roadmap

In this section, we summarize the advantages and disadvantages of the payment solutions introduced in Sect. 3 and present a roadmap for the future of payments in a DLT-based European economy. The presented solutions are not mutually exclusive. Instead, they will most likely co-exist in the future, leveraging their respective strengths. The time to market will differ significantly across different solutions. Figure 2 presents a systematic overview.

4.1 Time to Market for Different Payment Solutions

Panel (a) of Fig. 2 presents the situation in 2020. Payments triggered by smart contracts can be processed via existing DLT-based payment infrastructures. However, currently, the only available means of payment on such infrastructures are crypto assets such as Bitcoin, Ether, and stablecoins.[8] The market capitalization of euro stablecoins is negligible and—currently within the EU—there is neither legal nor regulatory certainty around stablecoins. MiCA will drive this development toward

[8] Some euro-denominated tokenized e-money solutions are already available or at least being developed. However, they usually only work in closed-loop environments without multibank capabilities.

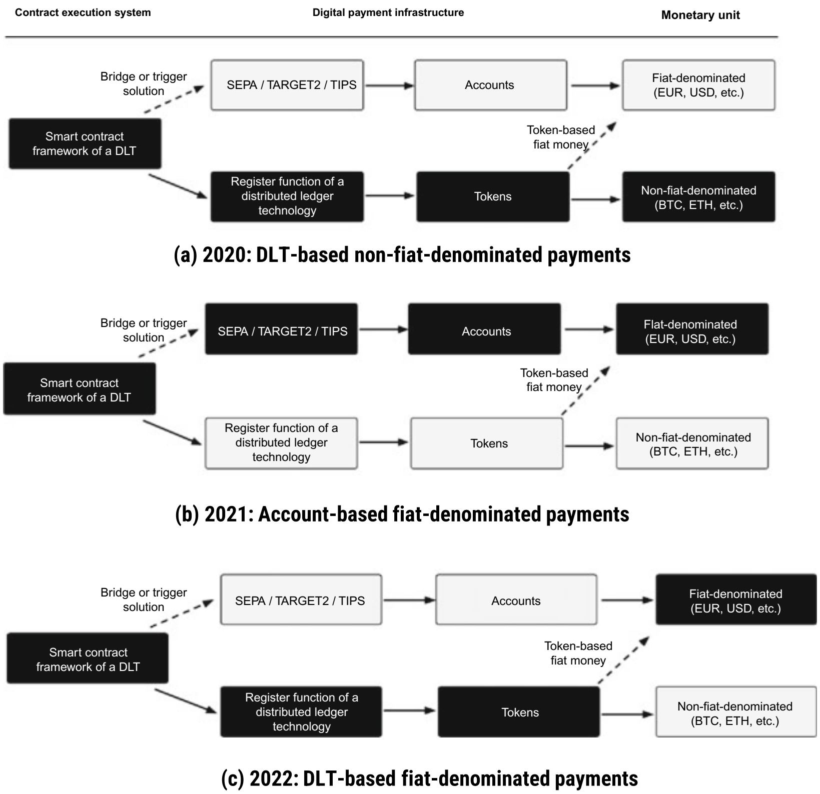

Fig. 2 Digital payments value chain in 2020, 2021, and 2022. *Notes* SEPA: Single Euro Payments Area; TARGET2: Trans-European Automated Real-time Gross Settlement Express Transfer System; TIPS: TARGET Instant Payment Settlement; DLT: Distributed Ledger Technology; BTC: Bitcoin; ETH: Ethereum. *Source* The authors

euro stablecoins becoming an adequate and uniformly regulated means of payment. Crypto assets such as Bitcoin and Ether are unsuitable as payment instruments for most DLT use cases due to their high volatility and low scalability. Consequently, there is a need for regulatory clarity and a stable, euro-denominated, regulatory-compliant payment solution.

Panel (b) of Fig. 2 illustrates how a bridge solution could help to achieve this goal in 2021. As discussed in Sect. 3.1, a wide range of use cases could be addressed by building a bridge between the DLT-based contract execution system and the existing account-based payment system. In particular, recent progress in processing real-time payments within the existing account-based payment system increases the potential number of use cases that can be accommodated using this bridge solution. Additionally, the introduction of an account-based CBDC could bring advantages by eliminating counterparty risk. However, with a bridge solution or an account-based CBDC that is not based on DLT, there remain challenges and limits with regard to cross-border payments, micropayments, seamless settlement (delivery-vs-payment) and "true" real-time payments that are transacted in less than one second. A major advantage of bridge solutions is that they are based on existing payment infrastructures and hence can be implemented in the short term. First DLT-based payments have been processed in test mode via bridge solutions in 2021 and will enter the market soon.

Panel (c) of Fig. 2 shows the scenario of a payment system that is capable of processing DLT-based euro-denominated payments. We expect such DLT-based fiat-denominated payments to be possible on a broad scale by 2022. To address the previously mentioned shortcomings and to realize further use cases, the euro must be integrated directly onto a DLT. There are three possible solutions: (1) EMTs, (2) sCBDCs, and (3) a token-based retail CBDC. These solutions would reduce—or even remove—the previously mentioned limitations. Therefore, use cases in the area of the machine economy, automated payments, tokenization, and cross-border payments would be operable without the limitations of account-based solutions.

4.2 Fungibility and Interoperability

Any token-based form of the digital euro faces two challenges: The tokens have to be fungible and interoperable. Fungibility means that tokens are indistinguishable from one another and interchangeable regardless of which institution issues them. This problem arises only in multi-issuer settings, that is, for EMTs and sCBDCs. In the case of EMTs, fungibility might not be ensured because even though all EMTs are subject to the same regulations, they might still be subject to the counterparty risk of the bank holding customer funds. In the case of sCBDCs, fungibility is achieved by backing the tokens 100% with central bank reserves. A token-based CBDC does not face the issue of fungibility because the central bank is the sole issuer. Interoperability refers to the ability of the contract execution system to interact with the digital payments infrastructure and the ability of different digital payments infrastructures to interact with one another. To circumvent the limitations of bridge solutions, the smart contract that triggers a payment needs to be based on a DLT that is interoperable with the DLT on which the euro is based. Since it is likely that smart contracts will be based on different DLTs in the future, we either require effective bridge solutions or a euro that is available on different DLTs.

4.3 Time to Market and Use Cases for Private- and Public-Sector Solutions of the Digital Euro

Which of the DLT-based euro-denominated payment solutions—EMTs, sCBDCs, or a CBDC—is best suited to facilitate the execution of and integration with DLT-based smart contracts? And when will they be operational? Fig. 3 presents a roadmap for the introduction of private- and public-sector solutions for the digital euro. Bridge solutions that connect DLT-based smart contracts with the euro in bank accounts are available in test mode since 2021 and will be brought to the market soon. Many of the existing use cases can be addressed based on this solution. To enable future use cases, such as related to micropayments, we need an "on-chain" euro.

The first version of such a euro could be issued in 2022 in the form of an EMT. One year later, we expect sCBDCs to enter the market. Both are private, multi-issuer versions of the digital euro, which will be subject to regulation that is currently being developed. While EMTs and sCBDCs face challenges related to fungibility and interoperability, they bring about one important advantage—enabling private institutions to issue a digital euro, in the form of an EMT or sCBDC, would allow to harness the opportunities and leverage the innovative capabilities of the private sector. Private-sector institutions are better equipped to develop payment solutions for a DLT-based economy. Leaving the issuance of tokens to the private sector facilitates a public–private partnership that exploits the comparative advantages of both sectors. The private sector (i.e., banks or other licensed intermediaries) is responsible for innovating and building intelligent solutions for end users. This includes technology choice, data management and regulatory compliance as well as customer onboarding, management, screening, and monitoring (including KYC and AML/CFT). The public sector (i.e., the central bank) focuses on regulation, supervision and financial stability.

A CBDC issued by the ECB is a single-issuer, public version of the digital euro. We do not expect a euro CBDC to be rolled out to the public before 2026. However, first tests with restricted user bases—similar to the CBDC project in China—could start as early as 2022. While a CBDC has advantages with regard to fungibility and interoperability, it might not be well suited to facilitate the execution of DLT-based smart contracts. First, introducing a CBDC takes considerable time. The demand for payment solutions for the DLT economy is increasing, and the first solutions will be needed soon. Second, the central bank does not have the necessary expertise and is not sufficiently agile to develop a token-based digital euro that caters to the fast-changing needs of the real economy. Third, and most importantly, the central

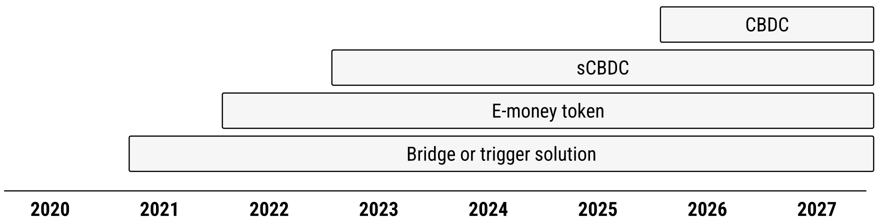

Fig. 3 Roadmap for future digital payment solutions. *Notes* (1) Fig. 3 presents a roadmap for the introduction of different payment solutions for the digital euro. Different versions of the digital euro will be introduced incrementally and will co-exist in the future. Private-sector solutions such as EMTs or sCBDCs are expected to be launched before a CBDC. (2) CBDC: Central Bank Digital Currency; sCBDC: Synthetic Central Bank Digital Currency. *Source* The authors

bank has concerns over disintermediating the banking sector because banks play an important role as intermediaries and credit providers in the economy. Therefore, the use of a CBDC will most likely be restricted (European Central Bank, 2020). Instead, a more appropriate use case of a CBDC might be to serve as digital cash. In other words, a CBDC could aim at replicating the characteristics of cash in the digital realm. This mainly includes being a risk-free and resilient means of payment that works independently of the private sector. Moreover, a CBDC should provide at least some form of anonymity that enables end users to conduct private transactions in a digital form if the use of physical cash significantly declines.

4.4 Interoperability and Efficiency

Finally, to conclude the analysis of the advantages and disadvantages of the payment solutions for the digital euro presented in this chapter, it has to be noted that each payment solution benefits from varying degrees of interoperability, efficiency, and integration. Figure 4 displays the four solutions presented in this chapter according to the two parameters of interoperability and efficiency. In perfectly interoperable systems, money does not need to pass a gateway to bridge between different payment networks, and an exchange from one type of euro to another type of euro (e.g., issued by another bank) is not required. In the short term, the bridge solution is best suited to achieve interoperability. The second dimension in Fig. 4 is efficiency. Once the euro becomes digital and can be traded with tokens representing other assets on the same

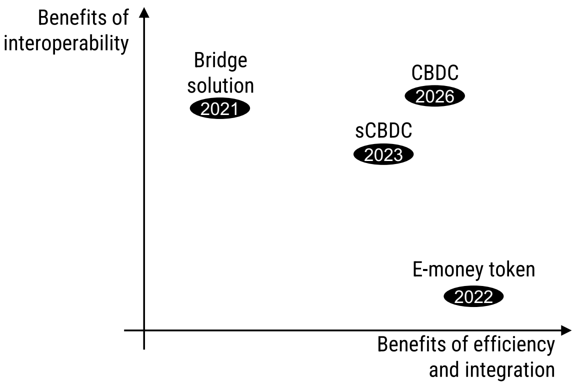

Fig. 4 Mapping payment solutions across interoperability and efficiency. *Notes* (1) Fig. 4 displays the payment solutions we present in this chapter in a two-dimensional graph. The first dimension reflects the benefits of interoperability. The second dimension reflects the benefits of efficiency and integration. The bridge solution yields high benefits of interoperability and low benefits from efficiency and integration. E-money tokens have the opposite profile. sCBDCs and a CBDC outperform other solutions with regard to the benefits but can only be expected to launch at a later stage. (2) CBDC, Central Bank Digital Currency; sCBDC, Synthetic Central Bank Digital Currency. *Source* The authors

DLT network, high-efficiency gains can be expected. For example, efficiency gains will be derived from the use of e-money tokens in the settlement of securities. The settlement of such trades would be more efficient as they would be executed entirely by computer algorithms, and no financial intermediary (i.e., a clearinghouse) would be required. Therefore, in the short term, e-money tokens are a promising means of payment for a DLT-based economy.

5 Conclusion

The aim of this paper was to respond to industry needs and the debate on the future of payments in a DLT-based European economy. We analyzed the most suitable euro-based payment systems to facilitate the execution of or integration with DLT-based smart contracts and estimated when these payment systems might become operational.

This chapter provides an analytical framework for the analysis of the payment infrastructure by dividing the digital payment value chain into three pillars; the contract execution system, the digital payment infrastructure and the monetary unit. We argue that the differentiation between these three pillars is essential since these core concepts, even though heavily interlinked, represent distinct parts of the digital payments value chain. For example, smart contracts will be implemented by industrial corporations and financial organizations, but they might not necessarily require that the euro is on a DLT-system at the same time. A short-term solution could be that the payments triggered by smart contracts (contract execution system) are settled in euro (monetary unit) through the current banking system (digital payment infrastructure). Payments in other domains such as international payments, the machine economy, or tokenization will require a different approach, where smart contracts trigger payments in euro (as a monetary unit) "on-chain." While in both examples smart contracts are essential and demanded by market participants, the digital payment infrastructures may vary according to the needs. Examples of other potential use cases are presented in the Appendix. For some use cases, the current banking system suffices as the digital payment infrastructure, and, for other use cases, a euro "on-chain" will be required. These examples illustrate that the benefit of the proposed differentiation between the three core concepts of the contract execution system, the digital payment infrastructure and the monetary unit is to provide a structured analytical framework for the debate about the future of payments in a DLT-based European economy. Furthermore, this three-pillar analytical framework is also universally applicable to discussions on digital payments beyond the European focus.

Guided by our analytical framework based on the three pillars of the digital payments value chain, this chapter identifies and analyzes four digital euro solutions for euro payments in a DLT-based European economy. The only solution utilizing existing banking infrastructure is a bridge solution connecting a DLT-based contract execution system with the legacy banking infrastructure. The remaining solutions that we identify—EMTs, sCBDCs, and CBDCs—involve integrating the euro within the

DLT-based infrastructure. There is a clearly identified need for an effective, interoperable, and regulatory-compliant euro-denominated payment solution compatible with DLT-based infrastructures. Finally, we lay out a roadmap for the future of payments in a DLT-based European economy.

Given current circumstances, we conclude that no individual payment solution will be sufficient to address all emerging use cases. Instead, a broad array of payment solutions will emerge and co-exist. It would be desirable to have the public sector, that is to say the ECB, launching a one-size-fits-all solution as soon as possible. This optimal solution would be a token-based CBDC. However, given the current discussions, it is unlikely that a euro CBDC will be implemented in the short term and that it will address all the challenges and needs of the market participants. Therefore, for the time being, a growing array of business models and use cases involving the digital euro will require a variety of diverse payment systems and solutions. There will be an increasingly complex world with the euro running on multiple infrastructures, including DLT systems, serving specific classes of use cases. We expect a broad range of payment solutions for multiple purposes to be launched at different points in time. Private-sector providers are currently exploring and developing such solutions.

However, the proliferation of private-sector solutions may also lead to a fragmentation of digital payment infrastructures in Europe and could raise issues of interoperability. While a variety of payment system solutions may address specific industry demands and cater to the emerging business models, lack of payment integration, and a uniform solution such as a euro CBDC may hinder the competitiveness of the euro and undermine the digital sovereignty of Europe. Given the strong network effects of payments, the race is on for a dominant payment solution capable of catering to the needs of a DLT-based European economy. The ECB may need to take a broader look at its mandate to meet the challenges of a DLT-based European economy and provide an alternative to potential foreign payment providers. European policymakers should also focus on providing adequate frameworks that support innovation in payment systems, mitigate risks and harness the opportunities in order to bring the DLT-based European economy of the future to the forefront in digital payments competitiveness and enhance Europe's progress toward strategic autonomy.

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Appendix: Use Cases for the Digital Euro

Internet of Things. Thanks to the Internet of Things (IoT), physical assets are turning into participants in real-time global digital markets. Gartner estimates that by 2020 there will be 20 billion connected IoT devices (Hung, 2017). Autonomous agents representing such IoT devices, machines, people, and organizations can interact with each other, communicate, negotiate, and transact in real-time. Blockchain and smart contracts enable these autonomous agents to become economic actors as they can be provided with an identity, a ledger to record their agreements, and a means of payment (Minarsch et al., 2020).

For example, turning traffic signs, charging stations, and electric vehicles into autonomous agents opens up new economic opportunities. Possibilities include an agent representing an electric vehicle that will be able to find and book a parking space and negotiate prices. The availability of real-time information, and the intelligence to analyze it, will make transportation systems more resilient and more efficient. Rerouting vehicles automatically around accidents, weather, congestion, and other delays have the potential to free up productive time for drivers and passengers (Hosseini et al., 2019).

As another example, energy management systems will benefit from the possibility of using reliable real-time information exchanged by software agents as well. Evidence exists that autonomous energy management systems for a smart home equipped with sensors can make use of the various energy consumption and production data to train agents using deep reinforcement learning (Ye et al., 2020). As a result, the agent gradually acquires the most promising energy management strategies by learning from repeated interactions through the process of trial and error. Once trained, the agent can react within milliseconds to autonomously respond to changes in the home environment in order to fulfill the homeowner's energy needs at the lowest possible price.

Transactions recorded on a distributed ledger will provide a permanent, immutable record of all activities. When coupled with machine learning and digital identities, this information can also be used to deliver additional layers of incentives for all participants in the network, including service providers and customers, and to build a reputation based on an immutable and reliable record of positive conduct and good performance. Ratings tied to the proof of delivered services can also be stored on a distributed ledger to build a comprehensive trust record that all network participants will be able to access on an open and permissionless basis. Connecting the ecosystem and enabling agents to securely transact with each other will enable a marketplace in which all stakeholders, ranging from vehicle owners to repair services to insurers to regulators and public safety agencies, can safely and securely exchange and analyze information in real-time. New business models will provide "insights as a service" that will let users unlock the wealth trapped in their transportation assets and data.

Automation. In the financial services industry, most of the automation initiatives that aim to increase process and cost efficiencies have typically targeted the conditional nature of financial products and contracts. This conditional nature refers to the construct of financial contracts in which subsequent decisions or steps (dependent conditions) in the inherent processes are predicated on the outcomes of the previous steps (precedent conditions). For instance, the payout of monthly interest in a bank savings account often depends upon both the amount of monthly balance maintained as well as the associated interest rate for that specific monthly balance. A higher monthly balance would typically attract a higher interest rate payout. Such conditional situations are omnipresent in financial contracts across banking, insurance, equity, debt and derivative contracts.

Using software code to automate such conditional dependencies and execute these transactions is not difficult. However, establishing the precedent condition between parties is a key inhibitor to successful and error-proof automation. For instance, a typical securitization transaction could include the following precedent condition—if the default rate crosses 10%, which can be followed by the following dependent condition—a 5% additional collateral needs to be deposited. In such a situation, the additional collateral can be secured with a digital euro. A DLT-based system can ensure that both the underlying conditions precedent and dependent conditions are not only accurately and transparently recorded but that the resulting action is automated through the use of smart contracts. As a consequence, DLT-based payments can also be triggered directly by the smart contract. DLT ensures that all parties have one single version of truth with no need for reconciliation or negotiations. With an immutable audit trail, for each transaction, the condition under which auto-execution happens is recorded, providing for easy audit and dispute resolution.

The logic of these use cases can also be extended beyond transactions. For instance, a key element of a central bank's role in managing monetary policy is to ensure that banks comply with cash reserve ratio (CRR) or statutory liquidity ratio (SLR) requirements, which can be automated using DLT-based means of payments. This feature can be even further used to automate many of a central bank's monitoring functions with dependent conditions providing not only triggers and flags but also the execution of subsequent actions.

Tokenization. The progressive tokenization of both digital and real-world assets works hand-in-hand with DLT-based means of payment. Notable examples include non-fungible digital art and collectibles (non-fungible tokens, NFTs) and cooperatives. By creating an NFT, an artist can register its copyright on-chain, protecting and proving provenance. Such artwork can also be tokenized into pieces, allowing individuals to own fractions of that artwork. For example, any person can probably and irrevocably own one-tenth of Picasso's Old Guitarist. Taking the concept further, such ownership could have built-in programmable allocative efficiency—leveraging the principles of the Harberger tax—but could also be entitled to one-tenth of all future profits generated by this artwork—whether it be reproductions, gallery showings or royalties. The sale profits would be automatically deposited in the fragment owner's wallet in digital euros, and the owner would be responsible for paying the tax in regularly required installments or risk losing ownership and resetting the tax rate. As per Harberger tax rules, someone else could at any point in time pay more than the person paid for the piece and thus own it henceforth, claiming the rights to future profits.

Digital blockchain-based cooperatives are already in full swing in several projects across Europe. These projects will tokenize any real-world asset and allow partial ownership of these assets. Such a cooperative can be a neighborhood that decides to collectively invest in a source of renewable energy. It can also be a set of completely unrelated investors investing in the fractional ownership of a building and earning parts of the building's rent proportional to the tokenized ownership they possess. In either case, transactions can be automatically executed to and from the investors, all of whom are dealing with a digital version of the euro. For example, as the euros for the building's rent drip into the building project's smart-contract-based address, the money is automatically distributed to all token holders proportionally minus maintenance fees. All token holders get automatic regular drips of income on their investment, and all renters have detailed insight into where their digital euros are being deposited and spent.

In theory, any real-world asset can be tokenized. This includes money, securities, bonds, shares, options, real estate, luxury goods (e.g., cars), works of art and private documents as well as information. Each such value can be represented as a token—a digital asset.

Cross-border payments. Token-based forms of money have the potential to transform cross-border payments. While current initiatives are focused primarily on domestic applications, numerous authorities have observed that initiatives around a digital euro have the potential to make cross-border payments more efficient and less expensive.

Several problems persist in the current cross-border payment model under which correspondent banks hold third-party bank deposits and provide those third parties with payment services. First, the number of correspondent banks has globally declined in recent years, leading to less competition and higher prices for customers. Second, correspondent banking is enabled through the pre-funding of correspondent bank accounts. This results in high compliance costs and lost opportunity costs. Additionally, this process limits the reach of efficient payment solutions to high-volume currency pairs and contributes to the high fees being charged to individuals seeking to send cross-border payments. Indeed, on average globally, currency conversions and transaction fees equal approximately 7% of the total funds sent (World Bank, 2018). Finally, the system itself is opaque and slow. Cross-border payments often take days to complete and are frequently fraught with execution risk, offering little communication or visibility to either the sender or recipient of funds.

Financial technology companies are in the process of exploring whether token-based payment solutions could reduce these limitations by enabling payments without the need to rely on the SWIFT network or correspondent banks. These offerings seek to improve existing payment infrastructures and link domestic payment systems to enable cross-border payments, including through reliance on DLT. Furthermore, interoperability is being explored. If the payment platforms being built (whether by the central banks themselves or through reliance on third parties in the private sector) are open and extensible, they may be able to deliver increased utility to users. The alignment of protocols across token-based payments (including a digital euro), private stakeholders, and cross-border payment networks could result in real-time instant settlement that is always available.

The practical impacts of these changes are potentially enormous. For example, a token-based payment solution coupled with an improved payment system could enable individuals to send remittances to their home countries cheaply and efficiently, where the funds can then be used to cover such living essentials as food, medical expenses and housing. Remittances can serve as a lifeline for the households to which they are sent (often rural and poor) as well as the larger communities in which those households live, which similarly benefit from the funds received. The successful deployment of a token-based payment solution could help ensure that more money is received by the individuals who depend on it the most.

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