UNIVERSITÁ DEGLI STUDI DI PADOVA

Dipartimento di Economia

Corso di Laurea Magistrale in Economics and Finance

TESI DI LAUREA MAGISTRALE IN ECONOMICS AND FINANCE

Tokenisation of Financial Assets

Relatore: Bruno Maria Parigi

Laureando: Francesco Marino

N. matricola: 2097009

Anno accademico 2024/2025

Dichiaro di aver preso visione del "Regolamento antiplagio" approvato dal Consiglio del Dipartimento di Scienze Economiche e Aziendali e, consapevole delle conseguenze derivanti da dichiarazioni mendaci, dichiaro che il presente lavoro non è già stato sottoposto, in tutto o in parte, per il conseguimento di un titolo accademico in altre Università italiane o straniere. Dichiaro inoltre che tutte le fonti utilizzate per la realizzazione del presente lavoro, inclusi i materiali digitali, sono state correttamente citate nel corpo del testo e nella sezione 'Riferimenti bibliografici'.

I hereby declare that I have read and understood the "Anti-plagiarism rules and regulations" approved by the Council of the Department of Economics and Management and I am aware of the consequences of making false statements. I declare that this piece of work has not been previously submitted – either fully or partially – for fulfilling the requirements of an academic degree, whether in Italy or abroad. Furthermore, I declare that the references used for this work – including the digital materials – have been appropriately cited and acknowledged in the text and in the section 'References'.

Firma (signature) ...Francesca Marino.....

DIPARTIMENTO DI SCIENZE
ECONOMICHE E AZIENDALI "MARCO FANNO"

DEPARTMENT OF ECONOMICS AND
MANAGEMENT "MARCO FANNO"

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

APPENDICE

Dichiarazione di autenticità [da inserire, dopo il frontespizio, nella prima pagina della Tesi di laurea o di laurea magistrale]

Dichiaro di aver preso visione del "Regolamento antiplagio" approvato dal Consiglio del Dipartimento di Scienze Economiche e Aziendali e, consapevole delle conseguenze derivanti da dichiarazioni mendaci, dichiaro che il presente lavoro non è già stato sottoposto, in tutto o in parte, per il conseguimento di un titolo accademico in altre Università italiane o straniere. Dichiaro inoltre che tutte le fonti utilizzate per la realizzazione del presente lavoro, inclusi i materiali digitali, sono state correttamente citate nel corpo del testo e nella sezione 'Riferimenti bibliografici'.

I hereby declare that I have read and understood the "Anti-plagiarism rules and regulations" approved by the Council of the Department of Economics and Management and I am aware of the consequences of making false statements. I declare that this piece of work has not been previously submitted – either fully or partially – for fulfilling the requirements of an academic degree, whether in Italy or abroad. Furthermore, I declare that the references used for this work – including the digital materials – have been appropriately cited and acknowledged in the text and in the section 'References'.

Firma (signature) ....

ABSTRACT

This thesis aims to investigate the structural, functional and regulatory dynamics of tokenisation applied in the context of financial assets, in order to evaluate its transformative potential within modern capital markets. The central research question focuses on how tokenisation, which is defined as the digital representation of traditional financial instruments such as equity, debt, real estate, and funds on distributed ledger technologies (DLT), can effectively enhance operations within financial infrastructure framework.

Key features of the technology such as DLT and smart contracts are examined in detail, paying particular attention on their ability to enable automate settlement and their function of reducing intermediary layers. Empirical findings highlight the tangible benefits of tokenisation, including reduced onboarding times, lower transaction costs, and improved liquidity. On the other hand, the analysis also addresses challenges associated with this technology, including interoperability, scalability and regulatory divergences across different jurisdictions.

Finally, the third section examines concrete real-world applications. Specifically, it explores the tokenised Real Estate Market, analyzes the case of Project Guardian, a multi-jurisdictional initiative led by the Monetary Authority of Singapore to test the use of tokenized assets in regulated financial markets, and assesses the application of tokenisation in the agricultural sector.

TABLE OF CONTENTS

INTRODUCTION

In recent years, the financial sector has undergone numerous changes driven by rapid advancements in digital technologies. Particularly, tokenisation has emerged as one of the most impactful, carrying the potential of reshaping the way financial assets are managed and issued. Based on the principles of Distributed Ledger Technology (DLT), tokenisation gives the chance of representing digitally traditional financial instruments on programmable infrastructures like blockchains, proposing to enhance transparency and efficiency of transactions, and improving accessibility to a higher number of individuals.

The aim of this thesis is to explore the concept of tokenisation with a particular focus on its structural foundation and how the process is concretely executed. Special attention will be given to core elements that enable it like DLT, Blockchain and Smart Contracts, examining how each of these components plays a crucial role in making tokenisation possible.

In order to provide a comprehensive understanding of the topic, the following chapters will highlight both potential benefits and challenges associated with the adoption of tokenisation within the current financial sector; particular emphasis will be placed on the examination of the regulatory system which plays a critical role concerning the institutional acceptance of tokenized approach. Finally, the attention will move to the assessment of case studies of real-world implementation in order to investigate the maturity and effectiveness within traditional financial sector.

CHAPTER 1:

Evolution and Infrastructure of Tokenisation Architecture

Tokenisation can be defined as the process of creating a digital representation of real-world or traditional financial assets such as equity, debt, real estate or cash on a programmable DLT platform. This digital representation is identified as token, and it has the ability of holding ownership rights linked to underlying assets. Moreover, it can be recorded, traded, settled and managed through the implementation of automated smart contract logic using a shared and immutable infrastructure (BIS, 2024; Agur et al., 2025; Disparte & Liao, 2024).

This chapter starts by outlining the traditional architecture of financial markets prior to tokenisation and the key drivers of the search for a more efficient and secure alternative. Thus, it aims to design the concept of tokenisation of financial assets describing in details its core technological enablers, DLT, blockchain and smart contracts, exploring how each component functions and contributes to the tokenisation process.

1.1 Evolution of the Concept of Tokenisation

Tokenisation is widely recognized as strictly connected to the blockchain ecosystem and the concept of DLT. Originally, the technology was ideated as a structural system for enhancing cybersecurity processes through the replacement of sensitive data with non-sensitive digital tokens for enhancing cybersecurity purposes. As a matter of fact, this technology was primarily introduced in payment processing, healthcare systems, and enterprise IT framework where the aim was to decrease the potential risk of data breaches and fraud for the users of the respective platforms. Providing a concrete example of this function, through tokenisation, the respective systems would not store an actual credit card number; instead, it would generate and store a token, such as TKN-984372 which is a placeholder that keeps the structure of the data, retaining the same format and length of the original information but not its underlying value. This makes the original data meaningless but still allows systems to work properly without exposing sensitive details.

Concerning this, these tokens are only meaningful when they are correctly associated with the original data through a highly secure and encrypted database known as a token vault. Specifically, the token vault has the role of a centralized and well-protected registry that keeps the exclusive correspondence between each token and its underlying data: this structure ensures that even tokens are intercepted, exposed or accidentally leaked, they cannot be derived or decoded, because of their randomised representations that have no mathematical relationship to the original values. It is important to highlight that access to the token vault is strictly limited to authorised applications or systems that operate under strict regulatory and compliance protocols (Lutkevich, 2023; Imperva, 2025).

Nowadays, the contribution of tokenisation is not only limited to the enhancement of cybersecurity, but it also finds proficient application through the financial market framework. In order to analyze accurately how properly the tokenisation process works, it is essential to identify and distinguish the core components that enable its effective implementation.

1.2 Distributed Ledger Technology (DLT)

DLT refers to a technological framework in which multiple data are synchronised and shared across a distributed network of nodes without the need for a central authority (BIS, 2025). A ledger is defined as a digital record-keeping system that continuously updates the database in which transactions or potential changes of asset ownership are registered.

The main function of DLT lies in the fact that, contrary to traditional databases managed by central intermediaries, this technology allows multiple parties to manage the access, verification and record transactions process under a detectable and immutable format.

As a matter of fact, DLT systems function as shared digital platforms where data is securely stored in a chain of blocks that are connected using cryptographic techniques. In this way, each time new information is added, it must be approved by the network that is in charge through a consensus process. This procedure helps to ensure that all copies of the ledger remain accurate and in sync across different participants (OECD, 2025). DLT serves as the foundation for the tokenisation of financial assets: as the modern financial systems demand higher transparency, operational efficiency and enhanced programmability, this technology offers a decentralised alternative to traditional centralised record-keeping systems.

Main elements of DLT

In order to fully understand how DLT works and why it serves as fundamental infrastructure for the tokenisation of financial assets, it is essential to understand its core components. Specifically, it is important to highlight how DLT is not a monolithic system, but rather a coordinated ecosystem which includes various technical and operational layers that work together to ensure decentralisation, security and transparency.

Nodes and Consensus Mechanism

Within DLT infrastructure, a node refers to any individual device, such as a computer or a server, that participates in the network by maintaining a copy of the shared ledger and, depending on its type, performing validation, communication or storage tasks (OECD, 2018). Nodes are crucial for delivering the operation of a DLT system because they have the role of collectively ensuring that data is accurately stored, verified and synchronized across all participants, without the need of relying on a central authority.

Concretely, each node operates with software that allows it to connect with other nodes, in addition to downloading the transaction history of the ledger and validating incoming transactions according to the rules of the specific DLT protocol, where examples can be Bitcoin or Ethereum. In detail, once a new transaction is proposed, the payment is sent out to the network; thus, nodes are in duty of independently verifying its legitimacy based on specific security criteria such as digital signatures or compliance implemented through smart contract logic. When the agreement is finally reached through a consensus mechanism, the transaction will be permanently added to the ledger.

Consensus mechanisms are defined as a set of rules within the computer network environments. These have the scope of helping participants work together in order to verify the integrity of any new information in electronic ledgers (Shafii, 2023).

The most essential nodes in the network are the Full nodes. As a matter of fact, they are able to verify independently the entire history of transactions once they occur, since they download and store copies of all of them. Full nodes are basically in charge of maintaining stability within the blockchain or ledger.

Secondly, Light nodes are essentially a lightweight version of full nodes: they have the ability to store only partial ledger data, and they depend on full nodes for allowing the transaction process.

Another possible kind of node is the Validator node which participates in the consensus mechanism by proposing and validating new blocks. Concerning DLT ecosystem, a block is defined as a digital container that has in duty a batch of data where mostly are groups of validated transactions (Ultimaco, 2024).

1.3 Blockchain: The most popular DLT Structure

Blockchain is defined as a specific type of distributed ledger technology where data are recorded in sequentially linked blocks in order to build an immutable and chronologically ordered chain. Moreover, each block is characterized by multiple transactions, a timestamp and a cryptographic hash of the previous block (World Bank, 2020).

Specifically, a timestamp in this context indicates a digital record that keeps track of the exact time and date of when a block is concretely added to the chain: in this way the technology proficiency can be enhanced through proving the order in which transactions occur, ensuring the transparency of the operations and consequently making the entire ledger chronologically traceable (Yaga et al, 2018).

A hash is the outcome of a cryptographic function, which is a mathematical algorithm that has the role of converting a specific input, such as a set of data, into a fixed-length string of characters. These are called hash value or digest. The main characteristic of this output is the uniqueness: In fact, even the slightest change in the input produces a radically different hash (National Institute of Standards and Technology, 2025).

It is important to notice how cryptographic hashes are deterministic which means that the same input will always generate the same output. Also, they are one-way functions: this feature is crucial since it does not give the chance to reconstruct the originally given input from the hash value (National Institute of Standards and Technology, 2025).

The primary goal of this mechanism lies in protecting data integrity within the blockchain system. In particular, hashes connect each block in the chain by embedding the hash of the previous block into the next one. Consequently, due to their deterministic nature and the one-way structure, it is possible to notice immediately if any data has been altered or deleted from an external individual without consensus (National Institute of Standards and Technology, 2025).

Blocks and Transactions in Blockchain

As mentioned before, in a blockchain structure, data are essentially grouped into blocks, where each of them contains different components. Specifically, each unit of blockchain is composed by a set of validated transactions which must be approved in order to be allowed correctly. Again, there is the presence of a timestamp that ensures that each older transaction precedes the new one. Furthermore, another element that plays an important role in blockchain function is represented by the occurrence of a "nonce". This short term, especially in a context of Proof of Work (PoW) system, stands for "number only used once", and it indicates a random or semi-random number that miners continuously change during the mining period in order to find a valid block hash (Yaga et al, 2018).

Specifically, this element represents the variable part of the block that each miner attempts to change in order to meet a specific predetermined condition called "difficulty target". Moreover, this last one can be expressed by obtaining a hash with a specific number of zeros that indicates a component of randomness. In particular, this procedure is useful in order to secure the generation of the block and consequently supervising data crypted from potential attacks (Yaga et al, 2018).

This mechanism is typical of the PoW system which is a consensus mechanism applied within blockchain networks in order to validate transactions and secure the ledger by requiring participants, defined as miners, to solve complex cryptographic puzzles.

According to this process, which is also known as mining, the first miner to find a valid solution has the role of sharing the new block to the network and, if it is accepted by the majority of nodes, then there is its addition to the blockchain (Nakamoto, 2008).

1.4 Different types of Blockchains

In the context of DLT, blockchain infrastructures are not always uniform between each other; actually, they may significantly differ in terms of accessibility, governance and level of decentralization. Concerning this, it is possible to distinguish three main categories of blockchains: public, private, and consortium.

Public Blockchains

Public blockchain represents a fundamental pillar of DLT and it is the most recognised form of blockchain architecture because of their association with cryptocurrencies such as Bitcoin and Ethereum. Specifically, public blockchain is a permissionless and fully decentralized digital ledger system in which anyone can take part without the need to require prior approval or authentication. This is connected with the fact that the open-access model implies that any user can read, write and potentially audit the data on the blockchain and in this way it is possible to contribute to both its democratic governance (GeeksforGeeks, 2024).

In detail, a public blockchain essentially is composed of a network of distributed nodes, where each of them is able to maintain a full copy of the blockchain itself. This links to the fact that, when a transaction is initiated by a participant, it is shared to the network where it is selected by validator nodes within the system. After, these validators divide the transactions into different blocks and successfully validate them through the chosen consensus mechanism such as Proof of Work (PoW) or Proof of Stake (PoS). Finally, once validated, the block is connected to the existing chain in order to compose a linear and chronological order (Ledger Academy, 2023).

It is notable how the key characteristic of public blockchains lies in their transparency and decentralization. As a matter of fact, since every participant has the chance of viewing the ledger and monitoring the transaction history, the need of a central authority is effectively removed. Nevertheless, in this framework security is guaranteed through cryptographic techniques and consensus protocols. Indeed, the attempt of a potential attack to the blockchain is challenging since it would require enormous computational resources or the ownership of the involved token and this would be linked with an enormous economical expense (Seth, 2024).

Analyzing the system from a technical perspective, public blockchains operate in trustless environments where each participant does not need to trust other ones or a central intermediary. Concretely, in the public blockchain framework, trust is established through mathematics and cryptography represented by the existence of digital signatures and hashing algorithms. For instance, once a transaction is signed with a private key, this can be verified by any other node via the adoption of the corresponding public one. This structure contributes to making the validation process open and transparent, consequently reducing fraud attempts and increasing accountability across systems (Singh, 2025).

One of the most famous cases of public blockchain adoption is provided by Bitcoin. In Bitcoin's network, miners tend to solve complex mathematical puzzles in order to be able to validate blocks; in this way it is possible to secure the network while also receiving newly minted bitcoins in addition to transaction fees as a form of incentives.

Nowadays, public blockchains are commonly adopted in a vast range of fields besides cryptocurrency applications. Regarding this, effective deployments include decentralised finance (DeFi) platforms, non-fungible tokens (NFTs), identity verification systems, supply chain tracking and even digital voting mechanisms.

Private Blockchains

Private blockchains, also defined as permissioned blockchains, are a specific kind of DLT ideated for being utilized within a closed network in which the access to the system is restricted to pre-selected participants. Opposingly to public blockchains, where it exists the possibility of joining the system, validating transactions and participating in consensus mechanisms freely, private blockchains require to obtain permission through authentication processes in order to engage with the network (Susniara & Smalley, 2025).

Concretely, a private blockchain is supervised by a single entity or a consortium of pre-approved participants. Accordingly to this governance structure, it is possible to enhance privacy by having an improved supervision over data management and consequently increasing general efficiency of the system (Susniara & Smalley, 2025). As a matter of fact, through this setup, the organization or the group in charge of the network has the chance to determine rights and responsibilities of each participant, then controlling who is able to take a vision and write on the ledger and implementing different protocols that are personalized with respect to the needs of the enterprise. In this framework, each node is previously verified before being allowed to join in the validation process of the transaction; similarly, the access is typically guaranteed by the use of private keys or specific credentials.

Analyzing the process under the functionality aspect, private blockchains operate not so differently with respect to their public counterparts but the consensus and accessibility processes show crucial differences. In this framework, participation is limited, and the created network is trusted. In addition to this and thanks to a limited number of components within the network, private blockchains have the advantage of being faster and more efficient in the employment and smoother consensus, such as BFT or PoS models (GeeksforGeeks, 2025). Moreover, another important aspect that is linked with the previous knowledge and verification of all the participants involved in the network is the easier alignment with regulatory and legal requirements that contributes to making private blockchain particularly efficient to implement for strategic sectors such as such as banking, healthcare and supply chain management (Seth, 2024).

Similarly, the adoption of private blockchain systems within financial sector is rapidly increasing since it allows to facilitate interbank settlements through the streamline of KYC (Know Your Customer) procedures and permits to optimize the digitalisation of asset issuance. Concerning this, JPMorgan's Quorum blockchain provides a prime example of a permissioned network tailored in order to optimize enterprise financial applications. The platform, bought by ConsenSys in 2020, is built on the Ethereum protocol and offers tailored privacy features and high processing capabilities in order to foster the protection for confidential transactions occurring between banks and institutional clients (Phemex Academy, 2021).

Consortium Blockchains

On the other hand, consortium blockchain is a specific type of permissioned blockchain that, opposingly with respect to the classic form of the system, is jointly managed by a group of different organizations, instead of being managed by a single entity (GeeksforGeeks, 2023). In particular, this mechanism permits to guarantee decentralization of authority but still keeping high level of trust and efficiency of transaction validation processes.

Consortium blockchains are particularly common and effective in cases in which multiple organizations must collaborate in order to share data between each other securely without exposing all information to the external world (Sharma, 2024). As specified before, the governance of a consortium blockchain is shared among all the entities that participate. Accordingly to its specific features, the main applications of this type of blockchain include banks due to its optimization of trading processes and interbank payments, and regulators since this technology offers an enhanced identity verification mechanism able to safeguard the security of the system.

Concerning the practical process followed by consortium blockchain, once a transaction is started within, the validation mechanism is handled by a predefined number of authorised nodes that create the group. In case in which the transaction fulfills the consensus rules, this will be added to the distributed ledger for being part of the pre-existent chain of blocks. The main difference with public system lies in the significantly lower energy consumption rate: this optimized energy performance is allowed by the presence of known and pre-approved validators that eliminates the need for energy-intensive mining processes.

Comparative Analysis between different types of Blockchains

The table indicated by Figure 1 shows a structured comparison between the principal blockchain architectures: Public, Private and Consortium. The analysis focuses on the assessment of six critical operational features: Permission, Access, Transparency, Security, Scalability and Efficiency, and Control. As a matter of fact, reviewing these characteristics, it becomes possible to realize how each blockchain type aligns with specific regulatory environments and organizational objectives.

FEATURE	PUBLIC BLOCKCHAIN	PRIVATE BLOCKCHAIN	CONSORTIUM BLOCKCHAIN
Permission	Permissionless	Permissioned	Permissioned
Access	Open to everyone	Restricted to authorized participants	Restricted to consortium members
Transparency	All transactions are publicly viewable	Transactions are not publicly viewable	Limited transparency, depends on consortium rules
Security	Highly secure due to decentralization	Secure due to limited access	Secure, but less decentralized than public blockchains
Scalability & Efficiency	Slower due to large network size	Faster due to limited users	Faster than public blockchains
Control	No central control	Controlled by a single entity or group	Controlled by a consortium of organizations

Figure 1: Comparative Analysis of different types of Blockchain (Rańda,, 2025)

Starting with permission, public blockchains are permissionless, and this allows any participant to be able to join and validate each transaction freely. Opposingly, both private and consortium blockchains are permissioned, meaning that only approved participants can gain access to the network and interact with it. Regarding this aspect, public blockchainsmaximal decentralization of the platform itself. On the other hand, private blockchains are more restrictive on the access, guaranteeing it only to authorized users that usually are part of a single organization. Instead, consortium blockchains offer an intermediate solution by allowing access only to pre-selected consortium members typically represented by a group of firms or institutions that are collaborating in order to reach a mutual benefit.

Analyzing transparency, public blockchains provides a complete vision of all executed transactions, which are publicly viewable and verifiable by anyone who decides to access to the platform. In contrast, private blockchains offer limited transparency: in this framework transactions are hidden from anyone who is not part of the authorized members. Once again, consortium blockchains offer an intermediate solution by providing conditional transparency that depends on the set of rules established by the consortium.

In terms of Security, public blockchains guarantee a high level of protection due to their decentralization function and thanks to its reliance on consensus mechanisms that allow to resist to potential attacks. On the other hand, private blockchains, even though still guaranteeing a notable level of security, depend more on the restricted access for users and are potentially more vulnerable to internal menaces or single points of failure. A single point of failure refers to any individual element such as server, node, network component, whose failure conducts to the breakdown or unavailability of the entire system or service (NIST, 2025). Finally, consortium blockchains offer an appropriate level of security as well, but since they are less decentralized than public ones, they are more vulnerable to potential issues among that may occur among consortium members.

About scalability and efficiency, public blockchains are generally slower. This happens due to the large size of its network and the computational complexity that is required for performing the validation process through its consensus mechanisms. Under this aspect, private blockchains shows more efficiency since the amount of nodes that participate to the network is inferior, and this contributes to leverage the acceptance of the blocks. In the same way, consortium blockchains receive the benefit from having a limited number of trusted nodes, permitting them to outperform public networks in speed and scalability, even maintaining a certain level of decentralization.

Lastly, as mentioned before, control within public blockchains is operated without the presence of a central authority. Opposingly, private blockchains are managed by a single entity or a specified group, and this guarantees full administrative power to the operator. Meanwhile, Consortium blockchains are controlled by a collaboration of organisations that ensure shared decision-making and governance within the network.

1.5 Smart Contracts

A smart contract is defined as a self-executing program which is stored on a blockchain, where the terms of the agreement between parties are directly reported using computer code (Ethereum, 2025). Once these contracts are effectively approved then they start to operate autonomously and this, when predefined conditions are met, leads to triggering predetermined outcomes.

The primary purpose of smart contracts is identified in increasing efficiency through minimizing the presence of intermediaries while offering tamper-proof automation for safeguarding digital transaction processes (OECD, 2025). In particular, regarding the tokenisation of financial assets, smart contracts have the role of encoding ownership rights, executing deep compliance controls in order to assure the security of the process and allowing real-time transfers through leveraging the transaction mechanism. As a matter of fact, their deterministic nature contributes to reducing settlement risks guaranteeing that, once the process is initiated, the contract follows exactly as programmed without the occurrence of potential issues.

Definition of Smart Contracts Features

In order to work efficiently, smart contracts require programming languages that ensure several crucial features*: determinism, security, resource efficiency and formal verifiability.* Particularly, these requirements are strictly linked with the fundamental nature of blockchain framework, where the code must run consistently and irreversibly across a decentralised network of nodes in order to result efficient.

First, *determinism* refers to the approach where a smart contract program must obtain the same output when the input remains unchanged, without showing any alteration produced by the time or the place of the execution. This feature shows a pivotal aspect of smart contract technology since a single deviation from the predetermined scheme would potentially turn in a consensus failure that would menace the integrity of the entire blockchain (Buterin, 2014).

Another core requirement that smart contract programming languages must pursue is *security*: As a matter of fact, the achievement of a safe network is the driver of high economic value. Typically, when a smart contract is published on blockchain, it cannot be changed and if there is any mistake reported in the code such as bugs or logic flaws, this can result in a permanent and irreversible financial loss. (Ethereum Foundation, 2025). A prime example of the impact of a code issue within the network is measurable through the Parity Wallet vulnerability case in 2017. Concerning this episode, a flaw discovered in a widely used Ethereum smart contract library caused the freezing of over 513,000 ETH (approximately $150 million at the time). In this case, the vulnerability was linked with an unexpected error within a function in the library contract, which mistakenly allowed a user to take control of the contract and subsequently deleting it: in this way that specific code stopped to work making all the stored funds permanently lost (Delmolino et al., 2016).

Another characteristic that is equally important regards *resource efficiency* due to computational and storage constraints imposed by blockchains: for example, Ethereum implements a gas mechanism in order to prevent denial-of-service attacks (DoS). In particular, concerning Ethereum framework, the term “gas” is utilized as unit of measurement for quantifying the amount of computational effort that is needed in order to perform operations on the network. Specifically, during the transaction phase the user will set boundaries defined as gas limit and gas price where the first refers to the maximum amount of gas unit they are willing to spend; on the other hand the second defines how much Ethereum unit they will pay in order to get one unit of gas (Ethereum Foundation, 2025).

Moreover, a Denial-of-Service (DoS) attack indicates the case in which someone tries intentionally to overload a system with an abnormal number of requests or operations in order to cause a crash or making it unusable for other users (Ethereum Foundation, 2025).

Finally, *formal verifiability* is the possibility of mathematical methods to check and prove that a smart contract behaves exactly as intended under all possible conditions, before its deployment on the blockchain. This feature is significant since, as mentioned before, smart contracts are immutable and play a crucial role in managing people funds. Regarding this, formal verification helps to prevent the occurrence of logic bugs or potential vulnerabilities which would have a large impact on the entire system (Tezos, 2025).

Analysis of Smart Contract Process

After the analysis of the key characteristics that define smart contracts, it is important to understand how these elements are applied into their practical implementation and operation on programmable blockchains.

Concretely, the operational workflow of a smart contract can be broken down into four main phases: Coding the logic of the agreement, deployment of the blockchain, Execution upon specific triggering conditions and state update of the network (Ethereum Foundation, 2025).

Coding the Logic of the Agreement

Within the first phase, developers start to define the terms and conditions of the interested contract and translate them into programmable logic through the most appropriate language according to their scope. As a matter of fact, their objective lies in codifying the legal or financial rules into deterministic code that can be automatically executed. A core element of this step is the development of functions, which design the permissible actions users can perform which may include transfer of tokens, the update of data structures or the development of specific protocol mechanisms. Regarding smart contracts framework, functions represent the instructor that defines smart contract's behavior. Specifically, they are triggered through transactions sent to the smart contract and each of them is programmed to verify the designed specific conditions decided before the execution.

Moreover, there are different types of functions that can be classified accordingly to their duties: View functions, Pure functions and State-changing functions (Ethereum Foundation, 2025).

First, view functions are purely designed for reading the current blockchain state without having the permission of affecting it.

On the other hand, pure functions do not even have the faculty of checking the current situation since they base their actions only on data that have passed them as an input.

Finally, State-changing functions are in charge of modifying the stored data contained inside the blockchain. Once one of these functions is correctly executed, the contract state will be officially changed and it will stay permanently recorded on the blockchain structure (Ethereum Foundation, 2025).

Alongside functions, developers have the duty of declaring new state variables, which are employed to be able to store data directly on the blockchain; commonly they are used to track information data regarding user balances, contract ownership or timestamps.

In order to enhance transparent interaction and traceability within the network, developers implement the so-called events that consequently will create logs whenever a specific action occurs. Nevertheless, despite the presence of logs does not affect the state of blockchain, it is crucial for the correct delivery of front-end interfaces concerning users' interaction with the system and of external application that have the role of registering smart contract activity in real time.

Furthermore, another pivotal element linked to a smart contract framework is the presence of modifiers. Concretely, their actions aim to enhance the security of the network by implementing access restrictions or designing precise pre-execution requirements that must be followed before functions are correctly executed. An example of their contribution might be represented by restricting the content of certain functions only to the contract's owner. Again, they have the ability to decide an enforcement of predetermined condition (like a time lock or balance threshold), which must be satisfied before the function executes (Solidity Foundation, 2025).

Deployment of the Blockchain

The deployment phase signals the moment in which smart contract switches from being a piece of code used for testing to a permanent and active entity on a blockchain. As a matter of fact, once the contract is written and the checking phase is completed, it is converted into a bytecode format in order to allow the blockchain structure to read and understand it.

In the context of smart contracts, bytecode refers to a low-level, machine-readable representation of the original contract code written by the smart contract developer. In order to allow the blockchain network to understand and process the human code that programmed the smart contract, this must first be converted into a bytecode format. In particular, this operation is delivered by a compiler: a specialized software tool that has the duty of translating the human (and higher-lever) code into an easier machine-executable one. The compilation process is crucial for minding the gap between the complexity of human logic and effective machine execution, ensuring that the smart contract's logic is correctly reported to the network in order to be executed faithfully.

Specifically, once the conversion occurs successfully, the generated bytecode is then included into a special transaction, called deployment transaction, that is sent directly to the blockchain network. The sole purpose of this operation is to publish the newly converted smart contract code on the chain. Moreover, this is processed like any other: it is exposed to verification process executed by network nodes, mostly validators, and if the control is delivered successfully it is inserted into a block. Moreover, once the transaction is confirmed, the blockchain builds a unique smart contract address. This has the function of identifier and enables users and other contracts to be able to find and interact with it (Ethereum Foundation, 2025).

Execution Upon Triggering Conditions

After the deployment phase is executed, it becomes possible to interact with the blockchain through its public functions. In order to be able to do so, users can send transactions to the contract's address to be able to communicate to the contract which action it has to be performed. It is notable that when someone wants to interact with smart contracts by sending a transaction, they automatically trigger a function. Thus, the payment is shared to all the nodes that participate within the network. At this point, the nodes that received will verify and execute the transaction, checking whether certain conditions coded in the contract, such as access rights or time constraints, are effectively met (Wood, 2025). Finally, if the transaction passes validation, then the function will be correctly executed, and each consequent change will be saved permanently to the blockchain's state.

This phase has critical importance for the entire smart contract process since it allows to keep the trustless and decentralized nature of blockchain systems. Once every node executes the same instructions and it turns to achieve the same outcome, then the network has the chance to reach consensus on the resulting state, which prevents potential disputes or possible attempts of manipulation.

Finality and State Update

This is the final phase concerning the smart contract process. Regarding this step, once a smart contract function is successfully executed and validated by the network, the eventual changes are finally recorded to the blockchain's state through a process known as state update. At this stage, the blockchain ensures that all the updates are permanently saved across all nodes that are part of the network. This is achievable due to the underlying structure of the blockchain ledger, which registers all data in a chronologically ordered chain of blocks where each of them is cryptographically linked to the previous one. Lastly, when the transaction is included in a block and that becomes part of the mentioned chain, the change is considered definite, and finality is achieved. In this particular context, finality refers to a state of acquired immutability where the outcome cannot be reversed or altered, even by the original contract creator (Ethereum Foundation, 2025).

CHAPTER 2

Benefits, Challenges, and Regulation of Financial Tokenisation

This chapter provides a comprehensive analysis of the benefits, challenges, and regulatory frameworks associated with the implementation of financial asset tokenisation. Drawing on industry literature, regulatory reports, and real-world use cases, it critically examines how tokenization may reshape financial markets and what must be addressed to enable its safe and scalable deployment. The goal is to offer a structured evaluation of the tokenisation landscape, offering insights not only into its transformative potential but also into the practical and legal foundations required to support its growth.

2.1 Current Impact of Tokenisation of Finanical Assets

In the middle of 2025, the tokenisation of financial assets, particularly real-world assets (RWAs), emerged as a transformative force within financial market infrastructure. Specifically, it is notable how the tokenised RWA market has reached approximately US $24 billion, where this value is driven predominantly by the private credit sector, which alone accounts for US$14 billion. This reflects an impactful 380% growth since 2022, indicating how fast-growing the institutional participation and operational maturity in blockchain-based instruments was in these last three years.

According to figure 2, McKinsey & Company projects that the market capitalisation of tokenised financial assets could reach US$2 trillion by 2030 in a base-case scenario. The report outlines a range of outcomes: from a pessimistic value of US $1 trillion to an optimistic one of US $4 trillion, without including cryptocurrencies and stablecoins.

Figure 2: Projection of market capitalization of tokenized financial assets

In particular, McKinsey identifies specific asset classes such as cash and deposits, bonds, mutual funds, ETFs and securitised loans, as most likely to embrace tokenisation mechanism due to their high regulatory compatibility with the process, their transaction volume and the respectively structural suitability for blockchain-based automation.

2.2 Benefits

Enhancement of Operational Efficiency and Elimination of Redundant Intermediaries

Operational efficiency represents one of the pivotal factors regarding the application of Tokenisation of Financial Assets.

Traditionally, financial infrastructures are heavily reliant on a significant series of intermediaries, legacy IT systems, and reconciliation processes, which may lead to potential issues such as latency, errors, and additional costs that have a considerable impact on the lifecycle of financial transactions (McKinsey & Company, 2024). Opposingly, Tokenisation enables the automation, standardisation, and simplification of post-trade processes by embedding asset logic into smart contracts and maintaining immutable records on a shared distributed ledger (LCX, 2024).

In conventional capital markets, activities such as clearing, settlement, custody, and reporting are handled by distinct entities such as clearing houses, custodians, brokers, and central securities depositories. It's important to observe that each operates independently and is able to maintain its own records. (OECD, 2025; Ekberg et al., 2022). Consequently, these fragmented ledgers result in time lags and reconciliation efforts that not only slow down transactions but also increase the risk of errors and disputes.

As noted by the Financial Stability Board (2024), tokenised assets aim to resolve this issue by allowing all transaction participants to access a single source of truth (SSOT). SSOT refers to a unified, authoritative ledger or database that all transaction participants can access, maintaining separate records, and all transactions are recorded on a shared, transparent, and immutable ledger (MuleSoft, 2025).

As highlighted by the OECD (2025), a blockchain ledger ensures synchronized and immutable records across the transaction lifecycle, removing the need for multiple intermediaries and significantly reducing the operational burden.

Moreover, McKinsey in its report titled *"From ripples to waves: the transformational power of tokenizing assets"*, outlines the potential positive impact of tokenization on financial transactions is measurable analyzing the reduction of errors in post-trade thanks to its real-time, shared ledger visibility and the implementation of smart contracts technology that unlocks the automation of transactions (Banerjee et al., 2024).

Smart Contracts and Automated Settlement

As mentioned above, one of the most significant advantages of implementing the tokenization of financial assets lies in the enhancement of settlement mechanisms. Traditional settlement processes rely heavily on intermediaries such as brokers, clearinghouses, and custodians, to manually verify and process the correct execution of the transaction. This approach introduces inefficiencies, leading to longer settlement times (T+2 or T+3 days), increased counterparty risk and costs due to intermediary fees. In parallel, traditional systems depend on paper-based or centralized databases, which are more prone to errors and security vulnerabilities (OECD, 2025).

With respect to this, tokenized financial instruments are often designed with embedded programmability, enabling them to self-execute certain conditions without human intervention. Moreover, figure 1 shows how transaction settlements can occur in near real-time (T+0) using atomic delivery-versus-payment (DvP) mechanisms (Rynes, 2023). Specifically, atomic DvP is important since it is a mechanism in which the delivery of an assets and the corresponding transaction occur simultaneously, and there is no scenario in which only one of the two parties involved does not fulfill their obligations. The term “atomic” symbolizes the indivisibility and irreducibility of the operation. This procedure is powered by the intervention of smart contracts, which have the role of automating several processes such as coupon payments, asset transfers, margin calls, or escrow releases, ensuring that transactions occur instantly and efficiently without delays or manual processing (Deloitte, 2024).

Another improvement regarding the execution of transactions through tokenization framework is pointed out by the loss of importance of intermediaries. Concerning this, in traditional financial markets, the post-trade process relies heavily on the role of the Central Securities Depository (CSD), a centralized institution responsible for the safekeeping of securities, the recording of ownership and the settlement of transactions between market participants. As reported in figure 3, with the implementation of tokenisation, the role of the CSD becomes increasingly redundant. As a matter of fact, tokenised assets are issued and recorded directly on the system where ownership and transfer are managed transparently and automatically through smart contracts. This decentralized registry model removes the need for a central bookkeeper, increasing the transparency and visibility of the transaction process.

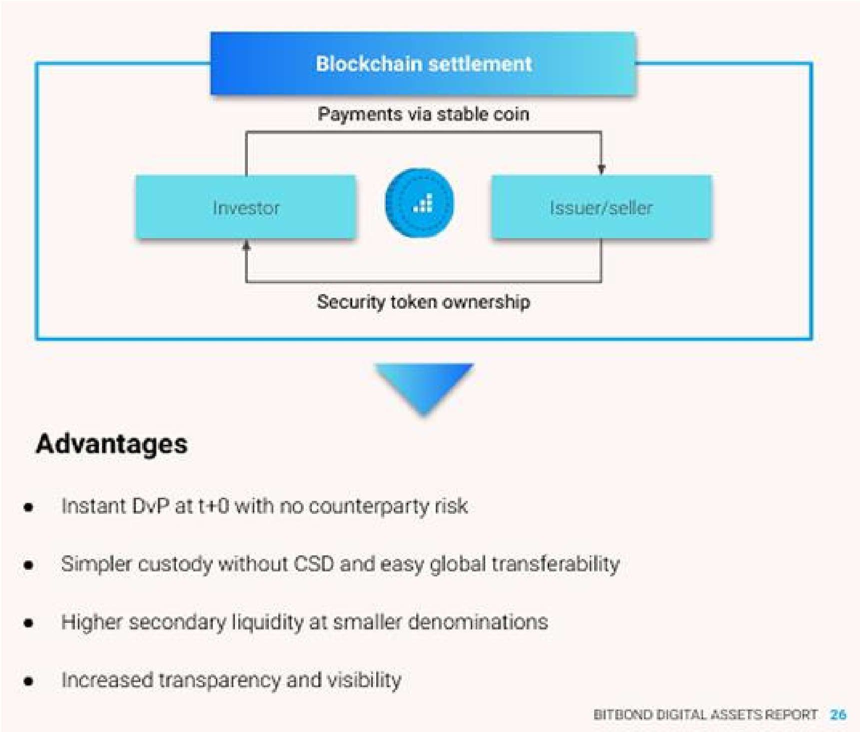

Figure 3: Settlement process in tokenised assets (Bitbond, 2022).

A compelling real-world demonstration of this concept is provided by Kinexys Digital Assets, J.P. Morgan's blockchain-powered settlement solution. This platform is structured to leverage blockchain and tokenised collateral to facilitate intraday repo transactions, enabling the exchange and settlement of collateral in a shorter amount of time (minutes instead of hours) (Ekberg et al., 2023). More specifically, the platform processes more than $2 billion in tokenized collateral transactions daily, where most of them are executed through intraday repo agreements (Rodrigues, 2025). According to JPMorgan, Kinexys can reduce operational complexity through the optimization of capital usage: in this way, the platform is able to drive efficiency into the repo market (Rynes, 2023).

Improved Liquidity and Fractional Ownership

One of the most transformative contributions of tokenisation to modern financial markets is its ability to enhance liquidity and facilitate fractional ownership of high-value and/or traditionally illiquid assets. In conventional finance, numerous asset classes including real estate, fine art, and private equity, suffer from low liquidity due to high minimum investment thresholds, regulatory frictions, limited buyer pools, and slow settlement cycles. Tokenisation addresses these inefficiencies by digitising ownership rights and enabling their division into smaller, more tradable units, thus broadening market access and facilitating active secondary markets (World Economic Forum, 2025).

A relevant aspect to consider is that tokenisation enables fractionalisation: the process by which an asset is divided into digital tokens, each representing a share of ownership. This feature shows particular value since it allows to decrease the minimum amount of capital required to participate in high-value investment opportunities. (Boston Consulting Group & ADDX, 2022).

A notable example is provided by ADDX, Asia's largest private market digital securities exchange. On this matter, ADDX leverages blockchain technology to obtain a 99% reduction in minimum investment size for private market products from USD 1 million to as low as USD 10,000, thus enabling access for a broader range of accredited investors (Kumar et al, 2022). This result is made possible via asset fractionalization via tokenisation. As mentioned, it is typical that investments in private market, including private equity, bonds and hedge funds, are structured with a minimum investments size measured around $1 million, necessary for the coverage of several offered services such as the manual management of these assets an associated legal constraint. Differently, ADDX allow the possibility of digitizing and dividing all these large investment products into multiple fractionalized tokens where each of them represents a small unit of the underlying asset, so allowing a larger number of investors to buy as little as a $10.000 within a fully regulated and compliant framework. This is made possible by the implementation of smart contracts technology, which introduces the automation of several key operational processes that dramatically lower the manual administrative work and reduce associated compliance costs. For instance, procedures such as the verification of investor eligibility through KYC and Anti-Money Laundering (AML) inspections, the execution of dividend payments and management of the investor accreditations are all inserted within the smart contract logic, enabling their automatic execution on the platform. In this way, tokenisation process helps to reach an increased efficiency level, permitting a broader number of potential investors to consider the possibility of negotiating on the platform. ADDX confirms how the adoption of smart contracts allows to move away from a model traditionally dependent on few and large institutional investors, supporting a more feasible and scalable financial infrastructure (Kumar et al., 2022).

Enhanced Secondary Market and Creation of New Markets for Illiquid Assets

Liquidity in traditional markets is often constrained by the absence of efficient secondary trading venues, particularly for alternative assets. As mentioned before, tokenisation enables near-instant peer-to-peer trading of fractionalized tokens in secondary marketplaces, which contributes to boosting asset turnover and improving price discovery.

A practical example of this is the enhancement provided by UBS. In 2022 the swiss bank issued a tokenised CHF 375 million bond on the SIX Digital Exchange and a blockchain-based settlement infrastructure. The bond settled instantly on-chain, and UBS reported that the deal reduced the complexity of distribution and created the foundation for more liquid digital bond markets (UBS, 2022).

Similarly, RealT, a U.S.-based platform where it is possible to negotiate tokenised real estate assets, allows investors to buy shares in rental properties via Ethereum-based tokens. These shares can then be traded on decentralised platforms, giving investors complete access to liquidity and enabling them to exit positions much more easily than through classical real estate mechanisms (RealT. 2025). This structure illustrates how tokenisation introduces a significant change in how property investments can be accessed and managed, especially by retail investors.

An additional compelling point is the monetization and trading of non-standard or non-bankable,non-interchangeable assets such as art, intellectual property, vintage cars, or even carbon credits. Indeed, by digitally representing financial assets on DLT, tokenisation enables these assets to be fractionalised, allowing them to be divided, traded and accessed in regulated environments. As confirmed by the European Central Bank (ECB, 2024), this structure significantly lowers the minimum investment threshold, thereby broadening market participation and democratizing access to traditionally illiquid or high-barrier assets such as private equity, infrastructure, or fine art.

A particularly illustrative example of this impact can be observed in the art market. Based on the *Art Basel and UBS Art Market Report 2025*, tokenised art transaction account for around US$1.1 billion while the traditional global art market reached a value of approximately US$65 billion in 2024. Despite it representing an emerging reality, this market has begun to establish a measurable presence showing a notable increase of nearly 40% year-on-year in this segment (McAndrew, 2025). Connected to this, according to the Bitbond (2022) report, tokenisation initiatives have led to growing interest in tokenised gold, art, and musical instruments from institutional clients and family offices. As the infrastructure matures, we are witnessing the formation of new asset classes that were previously difficult to package and offer through traditional financial channels.

A particularly interesting case is represented by tokenisation of sovereign debt. Specifically, the Republic of Slovenia successfully issued a €30 million digital bond via BNP Paribas' "Neobonds" tokenisation platform. Specifically, the bond is carriying a 3.65% coupon maturing in November 2024 and it was settled using central bank digital currency (CBDC) issued by the Banque de France. This experiment is recognised as the first example of sovereign bond tokenisation within the eurozone, and it has the scope of enabling broader investor participation, including smaller institutions and non-traditional buyers; while the volume of the transaction remaining modest, it represents a significant milestone in demonstrating both the technical feasibility and regulatory compatibility of DLT in sovereign capital markets (BNP Paribas, 2024)

Transparency of Transactions, Provenance Tracking and Ownership Verification

Transparency in financial transactions is a cornerstone of market integrity, regulatory compliance and stakeholder trust. However, in traditional financial systems, transparency is often limited by data fragmentation, manual reconciliation and information asymmetries across different parties (Deloitte, 2023). Tokenisation, by leveraging DLT, provides a fundamentally different infrastructure in which all transactions are recorded on an immutable, shared ledger, accessible in real-time to authorised stakeholders (OECD, 2025; Financial Stability Board [FSB], 2024). To drive interoperability and consistent transparency, industry stakeholders are converging on standards and frameworks. The Global Financial Markets Association (GFMA), for instance, advocates for a unified global regulatory framework to guide tokenisation initiatives, with a key focus on ensuring transparent, real-time reporting and cross-border compliance (GFMA, 2023).

Tokenisation helps to enhance the traceability process of asset provenance, linked to the ability to trace the origin, ownership history, and full transaction lifecycle of an asset across time (OECD, 2025). This feature is particularly beneficial in securities markets, where tracing the chain of ownership is essential for validating entitlements, enforcing rights and settling disputes. In traditional systems, such tracking may involve coordination across multiple intermediaries, with inconsistent or outdated data formats.

A compelling real-world example of tokenised provenance tracking is reported by Franklin Templeton's OnChain U.S. Government Money Fund (FOBXX): the first US Mutual fund that use public blockchain infrastructure for the recordkeeping of share ownership. Launched in 2021, the fund adopts DLT structure in order to enhance real-time transparency in the recording of share transfers and fund activity. Moreover, architecture allows regulators, auditors and investors to be able to access to a unified single source of truth, eliminating the need for traditional centralized reconciliation systems (Business Wire, 2023).

FOBXX operates under the regulatory framework of the 1940 Investment Company Act and invests at least 99.5% of its assets in government securities, cash or repurchase agreements fully covered by these instruments. Its investment objective is to deliver a high level of current income while preserving capital and maintaining a stable level of liquidity, targeting a stable $1.00 share price. Analyzing its performance, the fund has shown significant growth: in March 2023, the mutual fund reached a market capitalization of $270 million in assets under management (AUM) (Business Wire, 2023), and by the end of 2024, it had grown to approximately $410 million (Braun, 2024), establishing it as one of the leading tokenised investment vehicles in the financial market.

Access to Global Markets and 24/7 Investment

Tokenisation platforms are not only lowering entry barriers but also enabling round-the-clock access to global investment products, removing geographical and temporal constraints. Investors in different time zones can participate in tokenised offerings issued by institutions in major financial hubs like Singapore, Zurich, or New York, contributing to the liquidity improvement and enhancing the globalisation of capital markets (Synodus, 2024).

A prime example of the growing interest in the features offered by tokenised financial instruments is the partnership between Securitize and BlackRock in the launch of the BlackRock USD Institutional Digital Liquidity Fund (BUIDL). Introduced in March 2024, BUIDL represents BlackRock's first tokenised fund offering and is fully guaranteed by short-term U.S. Treasury securities, where each token is kept to a stable value of USD 1 (Sandor, 2024). The main objective of the fund is to leverage blockchain infrastructure to enable 24/7 trading, automated compliance and near-instant settlement for investors that decide to join. As result of these innovations, in less than two months since its launch, BUIDL has experienced an explosive growth that made it expand from a market capitalization of USD 40 million to over USD 450 million in AUM (Schonken, 2025).

The Federal Reserve Board (2023) notes that tokenised assets, especially those that are issued on permissionless blockchains, can be listed and traded 24/7, enhancing the appeal of financial markets to a new class of digital investors. Furthermore, through the elimination of multiple layers of intermediaries, tokenisation reduces costs and the necessary time for onboarding and Know Your Customer procedures through the adoption of blockchain-native tools to verify users once and avoid repeating the process across platforms. Concretely, according to the World Economic Forum, the adoption of standardized, on-chain digital identities automatically processed by the system can lead to up to a 90% reduction in onboarding costs for fund management and financial services, taking advantage from the automation of compliance tasks and streamlining client verification procedures (Block et al. ,2025).

Enhanced Market Integrity and Reduced Fraud

In traditional finance, issues as market manipulation, insider trading, and illicit flows are often enabled by the potential opacity and delay of reporting processes that may occur in financial transactions. Tokenisation mitigates these disclosure risks by providing a permanent and transparent record of every transaction, reducing information asymmetry.

A pivotal innovation supporting this ecosystem is Chainlink's Cross-Chain Interoperability Protocol (CCIP), developed in collaboration with ANZ Bank. Chainlink's Cross-Chain Interoperability Protocol (CCIP) offers the opportunity to send messages and transfer tokenised assets safely and in real time across different types of blockchains. What sets CCIP apart is that it doesn't just move tokens: in fact, the ecosystem also carries compliance rules with them. This implies elements such as transfer restrictions, regulatory checks, or specific event triggers (anti-money laundering controls or jurisdictional filters) are automatically enforced, even when the assets move across separate blockchain networks (Rynes, 2023).

In a 2023 pilot project with ANZ Bank, CCIP was used to demonstrate exactly what we mentioned: tokenised asset transactions were carried out with built-in compliance, marking how regulatory standards could be followed automatically as implied in the transaction itself. This shows an important step forward in building a global, interoperable tokenised financial system where transparency and regulation go hand in hand across different platforms and jurisdictions (Rynes, 2023).

2.3 Challenges

Despite its potential to transform capital markets, the tokenisation of financial assets faces several critical as that hinder large-scale institutional adoption. These challenges cover technical limitations, security vulnerabilities, and interoperability gaps, each posing significant barriers to efficient and secure implementation in real-world financial ecosystems.

Scalability Limitations in the Tokenisation of Financial Assets

One of the most pressing challenges to the mass adoption of tokenised financial assets is scalability: the ability to handle large volumes of financial transactions fastly, reliably, and at low cost (Chung et al., 2019). Despite DLT offers transformative potential in terms of decentralisation, automation, and transparency, its current performance limitations present technical and operational bottlenecks that hinder full-scale deployment across capital markets. Deloitte. (2024). In this regard, scalability issues are fundamentally linked to the transaction throughput of DLT networks. For instance, Public blockchains such as Ethereum are constrained by the number of transactions they can process per second (TPS). During peak periods, this limitation can result in network congestion, slower confirmation times, and higher gas fees, which are incompatible with the real-time demands of institutional-grade financial services. (OECD, 2020)

As Deloitte (2024) notes, infrastructure must be able to support low-latency and high-frequency trading conditions in order to support institutional tokenisation of equities, bonds, and derivatives. On the other hand, current DLTs generally fall short when compared with traditional clearing systems like SWIFT or FIX, which have the ability to process thousands of transactions per second with downtime close to zero (Chung et al., 2019). As a matter of fact, these infrastructures are capable of processing more over 100,000 transactions per second (TPS), with sub-second latency and virtually zero downtime, ensuring seamless performance under peak trading volume. On the other hand, public blockchains like Ethereum are typically able to support only 15–30 TPS. Instead, considering high-performance private DLTs the volume of executable transactions is higher but it still rarely exceed 1,000–2,000 TPS (Chung et al., 2019).

State Bloat and Data Storage Concerns

Another challenge linked to tokenization is the phenomenon of state bloat**:** the accumulation of transaction history on-chain, which leads to the exponential growth of the blockchain size and imposes higher storage requirements and synchronization workload on validators (Stellar, 2022). In fact, over time, this state may compromise the performance and decentralization of the network, requiring specialized hardware to participate in validation and thus centralizing control (Stellar, 2022). This has implications for the auditability and longevity of tokenised instruments, especially in asset classes like fixed income, where instruments may exist on-chain for 10–30 years. According to BIS (2024), unless long-term data scalability strategies are implemented, tokenisation could become operationally unsustainable over time. One of the core challenges associated with state bloat is the chance of overloading the full nodes within the network, which are responsible for maintaining a complete and up-to-date copy of the blockchain ledger. As the volume of on-chain data expands due to the accumulation of historical transactions, full nodes must implement larger storage capacities to accommodate the growing state size and this phenomenon brings to more difficult hardware and maintenance requirements and a consequent delay of the transaction validation process, due to the fact that nodes take longer to extract and verify the content of new blocks. Consequently, the latency of transaction process increases, negatively affecting the efficiency of the entire system: for example, in high-volume environments, this can result in a congestion of block production that may link to reduced performance for end-users which rely on immediate transaction settlements. (Alzoubi, Y. I., & Mishra, A., 2024).

Fragmentation Across Different Platforms

It's important to underline how scalability is not solely a technical issue: it is also architectural and structural. Regarding that, many institutions are currently operating through private or consortium-based DLT platforms that are incompatible with each other (Belchior et al., 2021). Thus, this issue creates the so-called "platform fragmentation", which limits the volumes at which tokenised assets can be traded, used as collateral, or simply be available for market participants.

As highlighted in Deloitte's April 2024 report, today, the major part of tokenised assets are not transferable outside the platform used to issue them, and in this way, the effect of network and scalability is considerably reduced. One of the direct consequences is linked to a lack of common interoperability standards, such as messaging protocols, identity layers, and consensus models, that prevent the creation of unified markets capable of operating at scale in an efficient way (Deloitte, 2024).

Interoperability Issues in the Tokenisation of Financial Assets

As tokenisation initiatives expand globally, interoperability has emerged as one of the key obstacles to the development of a cohesive, efficient, and globalised digital asset ecosystem. Interoperability in this context refers to the ability of different blockchain networks, tokenisation platforms, and financial market infrastructures to seamlessly interact, transfer, and settle tokenised assets across systems (Belchior et al., 2022). According to Belchior et al. (2022), the interoperability challenge is mostly based on the fact that different blockchains use different consensus algorithms, data structures, and virtual machines; these dissimilarities contribute to making the direct communication between platforms tricky, requiring mostly third-party bridges to facilitate transfers. This challenge is exemplified in Project Helvetia, a joint initiative launched by the Swiss National Bank (SNB), the BIS Innovation Hub, and SIX Group, in 2020 which aims to explore how tokenised assets could be settled in central bank money, particularly through the use of wholesale central bank digital currencies (wCBDCs).

The initiative follows a three-phase structure, where the third phase is currently in progress.

In Phase I, the project investigated two settlement models. The first one analyses the issue of wCBDC directly onto the SIX Digital Exchange (SDX) platform based on DLT, and the second one aimed to link the blockchain to the conventional Swiss RTGS system (SIC).

In Phase II, the project extended by integrating wCBDC into the core banking systems of participating commercial banks and then validating its use in realistic settings, including DvP and payment-versus-payment (PvP) transactions (BIS, 2022). This phase of the pilot is particularly meaningful as it implements the integration of wCBDC within the existing banking architecture, enabling seamless interaction with core functions such as transaction processing, payment settlement, compliance, and regulatory reporting.

Finally, Phase III is the first live pilot issuing wCBDC directly on a regulated third-party platform, enabling settlement of tokenised bond transactions (Jordan, T. J., 2024).

The results of the project confirm the feasibility of using central bank money in tokenised markets but they also highlight persistent interoperability challenges due to platforms with divergent governance, legal, and technical frameworks that struggled to communicate between each other in an efficient way.

Increasing of Security Concerns

We introduced how tokenisation is linked with the promise of automated and transparent transaction processes. Nevertheless, it is significant to observe how the introduction of distributed ledger technology goes hand in hand with new security risk issues that are specifically correlated to this framework, such as smart contracts vulnerabilities, cyberattacks, private key custody risks, and governance risks.

A landmark example of a critical vulnerability in smart contract execution is the DAO attack in June 2016. A Decentralized Autonomous Organization (DAO) is defined as a blockchain-based governance structure that operates without centralized leadership where the followed rules and decision-making processes are encoded into smart contracts logic. Concerning the case, the DAO (Decentralized Autonomous Organization) was an investor-directed venture capital fund deployed as a smart contract on the Ethereum blockchain that became the largest crowdfunding project of its time, raising over $150 million worth of ETH from more than 11,000 investors. However, a significant vulnerability within the smart contract code was exploited by an attacker and this allowed the attacker to transfer approximately one-third of the DAO's funds, equivalent to over $60 million, to himself (Zhao, X., Chen, Z., Chen, ., Wang, Y.,& Tang, C., 2017). Specifically, the attacked function called SplitDAO was programmed in the smart contract to let users withdraw their funds from the DAO. Theoretically, in order to secure the process, the function should follow a safe pattern where the first action is represented by the state update of the balance, followed by sending the funds as the final step. Opposingly, the function presented a bug that allowed it to send the money first and update the state of the balance afterward. Consequently, the hacker created a malicious contract with its own code, activating the SplitDAO function within the created contract in order to withdraw funds and, instead of waiting for the update of the balance, the attacker continuously called this operation in order to withdraw money without allowing the update of the state of the balance.

2.4. Regulation

One of the most significant barrier to the advancement of asset tokenisation is the lack of a clear and harmonised regulatory framework (Annunziata, Filippo, 2023). As tokenisation reshapes financial markets by converting real-world assets into digital tokens on distributed ledgers, its regulatory landscape remains fragmented and evolving. Nowadays, governments and financial regulators across the world are racing to create legal frameworks that foster innovation, market integrity, and investor protection (Philipp Maume, 2023).

European Union: MiCAR and the DLT Pilot Regime

The European Union has emerged as the jurisdiction with the most advanced and structured regulatory approach regarding the tokenised assets framework. In our analysis, we can distinguish between two different regulations: Markets in Crypto-Assets Regulation (MiCAR) and DLT Pilot Regime.

The Markets in Crypto-Assets Regulation (MiCAR**)** is a landmark regulatory framework adopted by the European Union in order to create a structured set of rules for crypto-assets across EU Member States, to bridge legal gaps and mitigate risks associated with the rapidly evolving crypto-asset market. MiCAR establishes definitions and supervisory structures for various types of crypto-assets, including asset-referenced tokens (ARTs), e-money tokens (EMTs), and other crypto-assets not previously covered by existing financial regulations. It also outlines specific obligations for crypto-asset service providers (CASPs), including authorisation requirements, governance standards, and disclosure duties aimed at ensuring market integrity and investor protection (EBA, 2024). MiCAR is supported by the European Supervisory Authorities, including the European Banking Authority (EBA) and the European Securities and Markets Authority (ESMA), which are tasked with developing regulatory technical standards and monitoring market developments. MiCAR got adopted in June 2023, with full application phases continuing into 2024 and beyond. As highlighted by the EBA, MiCAR represents a crucial step toward the EU's objective of fostering innovation while ensuring financial stability, particularly in light of the increasing interlinkages between crypto-assets and traditional finance (EBA, 2024).

On the other hand, The Distributed Ledger Technology (DLT) Pilot Regime, established by Regulation (EU) 2022/858, is a key legislative initiative of the European Union that creates a regulatory environment for experimenting the use of blockchain in trading and settling tokenised financial instruments. With respect to MiCAR, which focuses on crypto-assets not already covered by financial law, the DLT Pilot Regime applies specifically to traditional financial instruments (shares, bonds, and units in collective investment undertakings) that are issued and traded using DLT. The goal is to facilitate innovation while ensuring adequate investor protection and market integrity. According to ESMA's guidelines, entities that are willing to operate under the regime must meet comprehensive DLT Pilot Regime requirements on the size and type of assets admitted, in order to ensure safety to the framework. This regime is applicable across all EU Member States and supervised by National Competent Authorities (NCAs), where ESMA provides coordination and oversight through regulatory guidance and technical standards.

United States: Fragmented Oversight and Legal Ambiguity

In contrast to the EU's unified approach, the U.S. regulatory landscape is fragmented across multiple agencies. The classification of tokenised assets varies depending on the underlying instrument and the regulator's interpretation.

The Securities and Exchange Commission (SEC) considers tokenised financial instruments such as tokenised equities, bonds, and derivatives under the definition of "securities" as established by the Securities Act of 1933. Consequently, they are subject to the same regulatory requirements applicable to traditional securities, including registration, disclosure, and compliance obligations (SEC, 2024a). This classification relies on the Howey Test: a legal standard derived from the 1946 Supreme Court case *SEC v. W. J. Howey Co.*, which evaluates whether an asset involves an investment of money in a common enterprise with expectation of profits derived from the efforts of others (SEC, 2019).

Accordingly to the SEC, even tokenised versions of registered securities are correctly subject to disclosure and investor protection obligations, and entities dealing with them, such as trading platforms or custodians, must be registered as broker-dealers, alternative trading systems (ATS), or clearing agencies (SEC, 2022).

Differently, the Commodity Futures Trading Commission (CFTC) exercises regulatory authority in US primarily over the derivatives markets (such as futures, options, and swaps that are based on or involve digital assets), including tokenised financial instruments. According to the CFTC's official *Digital Assets Primer*, digital assets may qualify as commodities under the Commodity Exchange Act (CEA) and can also be regulated as swaps or other derivatives, depending on their structure and use (CFTC, 2020).

Comparative Analysis of EU and US Regulatory Approaches

Performing a comprehensive comparison between the regulatory frameworks of the European Union and the United States in the context of tokenised financial assets, we can notice a series of profound structural and operational differences that reflect divergent regulatory approaches.

Firstly, the European Union decides to adopt a dual-framework approach, consisting of the coexistence between Markets in Crypto-Assets Regulation (MiCAR) and the Distributed Ledger Technology (DLT) Pilot Regime. This aims to offer a harmonized and structured legal environment for both unregulated crypto-assets and tokenised traditional financial instruments. In contrast, the United States chooses to implement a fragmented oversight model, where regulatory authority is fragmented between different agencies such as the Securities and Exchange Commission (SEC) and the Commodity Futures Trading Commission (CFTC), leading to overlapping jurisdictions and a lack of unified legal clarity. Another point of divergence is represented by the regulatory methodology adopted. While the European Union adopts a comprehensive and forward-looking framework specifically designed for digital assets, the United States applies legacy legal structures such as the Securities Act of 1933 and the Howey Test mentioned before that follow interpretative enforcement on a case-by-case basis. This different vision is attributable to civil law approach chosen by EU laws which favors proactive regulation designed in order to foster innovation while maintaining legal certainty. Opposingly, the US conforms to common law system, where much regulation evolves through judicial interpretation and enforcement accordingly to precedent episodes and cases.

Observing in terms of market access and licensing, the EU has introduced explicit and purpose-built licensing requirements for crypto-asset service providers (CASPs) under MiCAR, which include clear obligations related to governance, transparency, and investor protection (EBA, 2024). In contrast, the U.S. applies legacy regulatory classifications, such as broker-dealer or alternative trading system (ATS), directly to entities that operate in the tokenisation framework, originated from a more cautious, enforcement-driven legal culture that builds on precedent cases rather than creating new statutes. As a result, U.S.-based firms face more regulatory ambiguity and higher compliance burdens, especially when blockchain-native models do not easily fit into existing categories.

A concrete example is provided by the SEC's lawsuit against Coinbase in June 2023, in which the Commission stated that Coinbase was operating an unregistered securities exchange by listing multiple digital assets that it considered to be securities. Opposingly, Coinbase argued that it had repeatedly asked regulatory clarity from the SEC, even regarding how to register properly, but was never provided with a workable framework or guidance for existing rules. The case shows the lack of specific legal regime for tokenised and digital assets in the U.S., forcing companies to navigate outdated regulatory classifications that are not designed for decentralized or blockchain-native platforms (SEC, 2023).

Finally, the European Union's regulatory approach offers more stability and stronger coordination between institutions, making it easier for market participants to operate with legal certainty. In contrast, the United States, despite its less clear regulatory framework, benefits from larger capital markets and quicker commercial adoption of tokenised financial products that allow US to be currently the biggest player in the tokenisation framework (Grand View Reserch, 2025).

Legal Classification in the Tokenisation of Financial Assets

As highlighted before, one of the main challenges to face in order to obtain mainstream adoption of tokenised financial instruments lies in the lack of a uniform and unique legal classification of tokenised assets. In more concrete terms, these are often perceived as conventional securities, debt instruments or financial derivatives but their digital nature on distributed ledgers points out legally-oriented debates regarding ownership rights, settlement recognition and the role of intermediaries in the market.

KPMG (2024) observes how tokenised bonds, even though they are functionally equivalent to traditional debt, require direct and explicit recognition in the securities law framework in order to guarantee that investors can legally claim repayments, receive interests and obtain complete protection by law. This lack is substantiated by the fact that, in the absence of clear legal definitions, token holders in the financial market may not be able to enforce claims in court, particularly in cross-border disputes or insolvency scenarios.

Germany's Electronic Securities Act (eWpG) offers one of the clearest legislative examples. Enacted in June 2021, eWpG provides a clear legislative framework for the issuance of electronic securities. Specifically, this law has the aim of allowing the issuance of securities in electronic form, eliminating the need for a physical certificate but still granting them the same legal status as traditional paper-based securities (BaFin, 2021). As a matter of fact, under this act, securities can be registered in either a central securities register or a crypto securities register, where the latter implements DLT to record ownerships and transfers. In this way, eWpG ensures that DLT-based registration fulfils the legal requirements of a security register, in order to make them legally safe and enforceable these electronic securities legally binding and enforceable (Squire Patton Boggs, 2021).

One of the most prominent users of the eWpG framework is represented by KfW, the german state owned development bank. In May 2024, KfW decided to issue a €20 million fully digital bond using D7, Deutsche Börse's blockchain platform, becoming the first institution to issue a central register security under the eWpG legal framework (KfW, 2024). Before, in 2023, KfW also issued crypto securities for a total value of €150 million on the Polygon platform through the use of blockchain technology, taking advantage of the crypto register option introduced by the same eWpG (Ledger Insights, 2023). Furthermore, in April 2025, KfW decided to invest in a €100 million digital covered bond called Pfandbrief issued by Berlin Hyp and recorded on the SWIAT blockchain, where the latter stands for Secure Worldwide Interbank Asset Transfer and it is a DLT platform developed in Germany that lets banks and institutions issue, record, and settle financial instruments on-chain (KfW, 2025). Another notable application occurred in January 2025, when Evonik Industries, one of the biggest chemical company in Germany, in collaboration with Deutsche Bank, issued a €500 million digital green senior bond via D7 platform, explicitly under the provisions of the eWpG, showcasing streamlined, end-to-end digital settlement. The bond is issued completely digitally through Deutsche Börse Platform and it is green since the raised capital is linked with environmentally causes and purposes. Finally, it is defined as senior since it guarantees higher claim in case of company default, resulting relatively safer for investors (Deutsche Bank, 2025). These issuances confirm the growing institutional confidence in the eWpG framework as a legally robust foundation for tokenised capital markets.

Future Regulatory Trends in the Tokenisation of Financial Assets

As the tokenisation of financial assets transitions from pilot projects to institutional deployment, regulatory frameworks are under growing pressure to evolve. While initial experimentation has occurred within regulatory sandboxes and under conditional legal interpretations, full-scale adoption demands a proactive, harmonised, and technologically responsive regulatory approach. Future trends in tokenisation law are expected to address the complexity of smart contracts, cross-border coordination, platform interoperability, digital custody, and liability structures.

A major trend in financial regulation is the shift from a form-based approach (focused on the nature of instruments) to a function-based and risk-based approach, where regulators assess tokenised instruments by their economic function and systemic implications. The evolution from principle-based to risk-based regulation in financial markets is being actively explored by the Federal Reserve. This shift has the aim of recognizing the unique challenges posed by decentralized, programmable financial instruments and looks for adapting regulatory frameworks accordingly.

Building on this, a joint initiative by the New York Federal Reserve and the Bank for International Settlements, known as Project Pine, examined the feasibility of conducting monetary policy operations within a tokenized financial system.

The pilot project specifically aimed to test if central banks could use smart contracts and tokenized assets to conduct operations such as repurchase agreements (repos), interest payments and collateralized lending in an effective way, guaranteeing automated processes and security. Using a prototype where built and developed on a permissioned blockchain infrastructure in order to simulate how a central bank might operate adopting blockchain and smart contracts technology, Project Pine simulated ten different monetary policy scenarios, including liquidity provision, interest rate changes, and asset purchases, with smart contracts automating the operational logic (Federal Reserve Bank of New York, 2025).

Analyzing the case, it is noted how the system enabled near-instantaneous execution of monetary operations, significantly enhancing the reactivity and efficiency of policy transmission. In particular, the prototype was able to achieve sub-second execution latency across all ten scenarios, while maintaining accurate calculations regarding collateral and interests (BIS, 2025). These results are encouraging since, in traditional financial systems, these operations can take minutes, hours or even days, especially when done manually or across multiple institutions. As matter of fact, it is evidenced how central banks could become quicker and more flexible in reacting to macroeconomic conditions through the implementation of tokenisation. Although the initiative was only a conceptual exploration, it provided concrete evidence that tokenized financial infrastructures could support the core functions of monetary policy, accordingly to a consequent evolution of regulatory framework as well (Derby, M. S., & Jones, M. , 2025).

CHAPTER 3

Tokenisation of Real Estate Assets and Applied Cases of Tokenisation

The following chapter aims to explore the practical applications of asset tokenisation through the analysis of interesting real-world case studies that demonstrate its transformative potential across various sectors of the financial and real economy. The first section is dedicated to introducing the tokenisation of real estate assets framework, pointing out the mechanism under a technical and operational perspective. The chapter then progresses to review notable applied cases of the technological implementation, such as institutional pilot project called Project Guardian, highlighting how this is making changes across ecosystems of actors, platforms and regulatory approaches. Finally, the focus is given to the Agrotoken-Santander experiment in Argentina, which represents a pioneering model for agricultural finance through tokenised grain-secured lending.

3.1 Tokenisation of Real Estate Framework

As mentioned in Chapter 3, one of the most compelling applications of tokenisation lies in its capacity to reshape traditionally illiquid and operationally rigid markets. Among these, the real estate sector stands out as one of the most promising domains, in which distributed ledger technologies can be able to potentially unlock new levels of efficiency, accessibility, and investor participation on the market.

Stepping back to consider the broader context, the real estate market has historically presented significant barriers to entry for average investors, primarily due to substantial capital requirements and complex investment structures, with minimum investments requirements typically starting from $25,000 and potentially rising to $100,000 or more, making them accessible predominantly to high-net-worth individuals and institutional investors. This high financial threshold effectively excludes many individuals with limited capital from participating in real estate investment opportunities (Brown, J. R., 2025).

Concerning this, real estate tokenization has the potential to break down traditional barriers to property ownership. Indeed, tokenisation of real estate assets enables the division of property ownership into digital and fractional units, significantly decreasing the entry barrier and opening new opportunities to average investors. Notably, this implementation helps to achieve portfolio diversification that improves potential risk-adjusted returns. Moreover, by leveraging blockchain infrastructure, investors can negotiate these tokenised shares on secondary digital marketplaces, so enabling greater flexibility and reducing friction in the investment lifecycle. Meanwhile, real estate developers and asset managers have the chance to benefit from optimized management processes, marking a fundamental shift in how real estate capital markets operate (Oyelabs, 2024).

According to Figure 4, the tokenization of real estate assets is projected to expand significantly, reaching a total value of tokenized underlying real estate assets expected to touch $4 trillion by 2035, starting from a $0.3 trillion value registered in 2024, representing a compound annual growth rate (CAGR) of 27%.

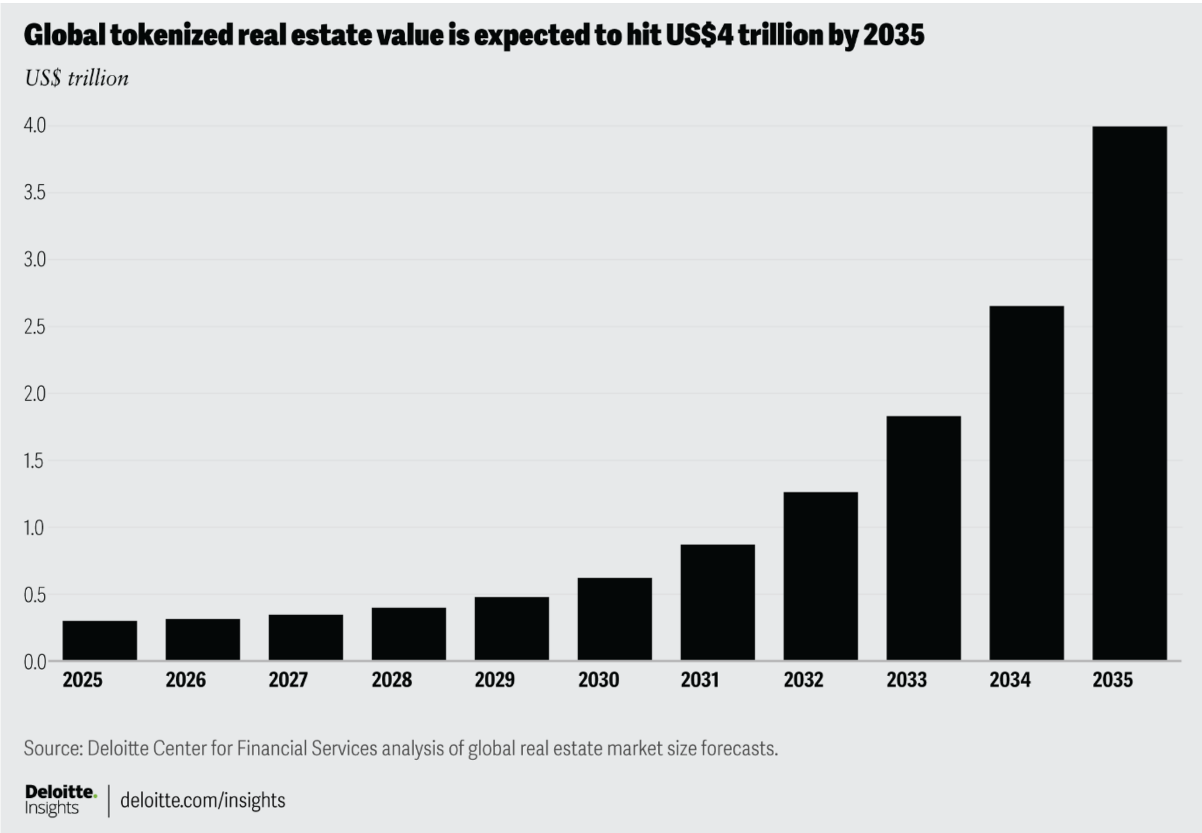

Figure 4: Projection of Global tokenized real estate value by 2035 (Deloitte, 2025)

According to this projection made by Deloitte, the growth will be driven primarily by three segments: tokenized private real estate funds, tokenized ownership of loans and securitizations and tokenized undeveloped or under-construction properties.

Specifically, tokenized private real estate funds are forecasted to reach $1 trillion with a market penetration rate of 8.5%; tokenized loans and securitizations are expected to amount to $2.39 trillion, with a penetration rate of 0.55%; while tokenized ownership of undeveloped land and projects is projected to reach $50 billion, with a penetration rate of 0.80%. These figures result from a structured meta-analysis of global real estate market size forecasts, in which Deloitte applied estimated tokenization penetration rates divided for each subsector. The methodology is essentially based on assessing "key subsegments of the industry" and applying impact assumptions tailored to each, and using cases across commercial real estate verticals. The result of this predictive approach reveals how tokenization could enable expanded investor access through enabling streamlined operations which may link to an increased market offering.

3.2 How does Tokenisation on Real Estate Assets work?

Tokenisation operation of a real estate asset through blockchain requires a well-structured, multi-phase process that has the aim of integrating legal, technical, and financial operations in order to convert physical ownership of the property into digital tokens, which accurately represent the composition and the value of the underlying asset. As previously mentioned, this mechanism is organized into multiple stages (Gupta, 2020).

Asset Identification and Due Diligence

The first step concerns the research of suitable real estate, whether commercial, residential, or mixed-use, that has clearly defined ownership and well-designed legal structure. Commercial real estate comprises properties utilized for business-related purposes, primarily to generate income through leasing or capital appreciation (Seth, 2024). Residential real estate includes properties designed and zoned for people to live in, encompassing both owner-occupied and rental dwellings (Martin,E. J., 2022). Mixed-use real estate refers to developments that combine residential, commercial, and sometimes industrial components within a single property or development area (Federal Reserve Bank of Minneapolis, 1998).

Due diligence refers to the comprehensive legal, financial and technical evaluation conducted in order to ensure that the ownership is effectively suitable for the digital token issuance and that the associated risks are appropriately mitigated. This analysis involves aspect such as title research, real estate valuation and legal verification in order to assess market value and ownership status correctly, to proceed with token issuance (FCIQ, 2025).

SPV Formation

Another crucial phase that facilitates financial tokenisation of Real Estate assets is the establishment of a Special Purpose Vehicle (SPV). In this context, SPV represents a legally distinct entity, such as a limited liability company (LLC) or partnership, established typically to own and isolate a specific asset or project, thereby keeping risks and legal responsibilities of one specific project or asset separate from the rest of the company or its investors (Investopedia, 2024). Specifically, the SPV has the duty of holding the legal title to the property, enabling the issuance of digital tokens that reflect fractional ownership or potential economic rights regarding a specific underlying asset. This structure is convenient and widespread since it ensures legal and regulatory clarity, as well as protection to investors by limiting their exposure to the asset held within the SPV itself (The Bulldog Law, 2025). Therefore, this legal entity acquires the role of legal owner of the property, and it is structured to isolate the asset from the promoter's balance sheet.

The formation of a Special Purpose Vehicle (SPV) for real estate tokenisation follows a well-structured sequence of steps. The first one is the correct definition of the SPV's purpose: this has to defined as owning a single real estate asset in order to allow the issuance of tokens that represent the fractional ownership of the asset itself (Antier Solutions, 2025). Again, an important part is the choice of jurisdiction based on regulatory clarity and tax efficiency. The common choices in this case include Delaware in USA and other investor-friendly jurisdiction (Faster Capital, 2025). As a matter of fact, Delaware regulation is generally appreciated as an investor-friendly jurisdiction because of its robust legal framework, confidentiality attributes and tax neutrality. One of its key advantages lies in the presence of the Court of Chancery: a specialized judicial body that has in duty to handle corporate disputes efficiently and without the presence of juries. Additionally, the Delaware General Corporation Law (DGCL) is also highly flexible, facilitating simplified structures and governance of SPVs while safeguarding investor interests (Haberly, Wojcik, 2017). Therefore, the SPV is formally created by filing incorporation documents, such as articles of incorporation and operating agreements, describing the SPV's name, purpose, capital structure, and governance (Syndacately, 2023).

Digitisation of assets

The following phase of digitization regards the issuance from the created SPV of the shares, that will consequently be tokenised. Concerning this, after the legal setup, the equity or income rights of the SPV are digitised using blockchain-based smart contracts, whereby token's properties, such as voting rights, income distribution mechanisms, transfer restrictions and compliance rules will be defined. It's crucial to highlight that these tokens can represent ownership rights, dividend claims or participation in profits, depending on which kind of investment model is adopted (equity, debt, or hybrid).

Equity tokens in real estate tokenisation represent fractional ownership in the SPV that legally holds the underlying property asset, where investors become indirect co-owners of the property, achieving the access to a proportional share of the rental income generated by the asset itself, as well as any future capital appreciation (Wilson, 2023).

Opposingly, debt tokens represent a form of digital loan agreement extended to the SPV that owns the underlying property, that has the aim of offering investors the opportunity to act as a lender and receiving fixed-income returns rather than ownership of the asset. It is important to notice how debt token holders do not possess ownership rights in the asset or the SPV, nor do they participate in governance decisions, as they function strictly as creditors rather than equity stakeholders. Nevertheless, their purchase allows holders to be exposed to predefined interest payments over a set period and to the repayment of principal at maturity, similarly to traditional bonds or promissory notes (Wilson, 2023).

Finally, hybrid tokens are designed in order to combine features of both equity and debt instruments, being able to offer investors a balanced exposure to both income stability and potential capital gains. These tokens may be structured as convertible debt, preferred equity, or as instruments that include a fixed base return in a way that is similar to interest payments, combined with performance-linked bonuses derived from rental income or property appreciation (Wilson, 2023).

Token Issuance and Platform Integration

Analysing the operational implementation of the digitisation process, the smart contract is executed on a blockchain; consequently tokens are minted in proportion to the reference point represented by the value of the underlying asset. Providing an example: supposing to have a $10 million asset that is tokenised into 1 million tokens; at that point each token represents $10 worth of value. Moreover, these new issued tokens are listed on a compliant Security Token Offering (STO) platform where accredited or retail investors can purchase them. STO is a regulated fundraising process in which a company has the chance to issue digital tokens on a blockchain that represents rights to real-world assets, such as equity, bonds, real estate, or other investment instruments. Therefore, STO tokens are legally classified as securities so they must comply with existing securities laws, providing investor protection like due diligence process, Know Your Customer (KYC) checks and regulatory oversight (Mad Devs, 2024). Referring to this, in the context of STOs, KYC refers to a mandatory compliance process that requires to issuers and platforms the verification of the identity of investors in order to assess their risk profiles and ensure their legitimacy before allowing them to purchase any tokenised securities. This process is typically carried out through the collection and verification of personal identification documents, giving the proof of their addresses, and controlling eventual sanctions or presence in regulatory blacklist, such as politically exposed persons (PEPs) or individuals flagged AML violations (Notabene, 2024).

Investor Subscription and Capital Deployment

An additional critical step in the process regards the subscription phase, where investors decide to commit their capital fiat money or cryptocurrency payments. These funds are then directed to a SPV or fund structure that acquires and manages the underlying real estate assets. Once funds are deployed to the SPV, the issuance of security tokens begins. As described by Deloitte and Baker McKenzie (2022), this is the part of the process where blockchain technology plays a critical role: as mentioned tokenised shares are issued and recorded on a distributed ledger and this ensures immutability, transparency and programmable compliance such as whitelisting and dividend distribution rights.

In the context of financial asset tokenisation, the whitelisting process refers to the phase that determine the approval of investor that have passed KYC and AML checks, ensuring that only verified participants can engage with specific tokens (Coinbase, 2025).

Finally, the investor will receive tokenized certificates of ownership which may be tradable on regulatory secondary markets.

Post-Issuance Management and Secondary Market Liquidity

As we described before, once investors subscribe to a tokenised real estate offering, they will receive security tokens that represent a fractional ownership interest in the underlying asset such as residential or commercial property. Therefore, smart contract implementation plays a pivotal role in this structure by automating income distributions of monthly rental yields directly to token holders, based on their proportional stake in the property. For instance, platforms like RealT and Debut Infotech implement smart contract logic that pays out earnings in stablecoins like USDC to the investor's digital wallet, accordingly to rental proceeds generated by the tenants of the property (Debut Infotech, 2024). Specifically, USDC is a type of stablecoin, a digital asset that is pegged 1:1 to the US Dollar: this means that 1 USDC is always intended to be worth exactly 1 USD (Circle, 2025).

It's interesting to notice how, in cases where the real estate is a commercial asset like a hotel or multifamily complex, income may include not only the rent but also additional profit-sharing from other operations. A prominent example of this is the Aspen St. Regis Resort tokenisation, one of the first high-profile Security Token Offerings (STOs) supported by a luxury hotel. In 2018 Elevated Returns, a New York-based asset manager, launched Aspen Digital (AspenCoin), a digital security representing a 18,9% ownership stake in the St. Regis Aspen Resort, a five-star property in Colorado. Through the sale of 18 million tokens at $1 each on platforms such as Indiegogo and Templum Markets, the project successfully raised $18 million from several accredited investors (Aspen Times, 2018; Security Token Market, 2023). AspenCoin was structured as a revenue-sharing equity token, where holders were entitled to receive periodic distributions linked to the hotel's net operating income, and not fixed rental payments. Additionally, Elevated Returns introduced an "Owner Benefit Program": within this structure investors that were holding at least 10,000 tokens for over 30 days had the chance of receiving up to 50% cashback on personal stays at the resort. This initiative had the aim of effectively aligning the interest of investors with the operational success of the asset (Security Token Market, 2023). Moreover, after the issuance, AspenCoin Started to be traded on digital marketplaces such as tZERO, achieving a realized capital gains via the appreciation of the price, with the token reaching values as high as $2.70 during 2023 (STM Market, 2025).

Interestingly, the issuance of AspenCoin was structured in order to adhere with U.S. securities regulations, specifically under SEC Regulation D Rule 506(c). In particular, this is defined as a provision under U.S. securities law which allows companies to raise unlimited capital from private offerings while publicly advertising the investment, once is proved that all purchasers are verified accredited investors (SEC, 2024). As mentioned above, participation in the Security Token Offering (STO) was restricted to accredited investors. These individuals were required to be involved in a rigorous verification process in order to confirm their eligibility. This procedure involved the need to provide valid documentation to prove either an annual income that exceeds $200,000 (or $300,000 jointly with a spouse or a net worth value of at least $1 million, not taking into consideration the primary residence. The verification and onboarding process is facilitated through specialized platforms like Templum Markets, a Financial Industry Regulatory Authority (FINRA) and SEC-registered broker-dealer, in which Know Your Customer (KYC) and Anti-Money Laundering (AML) procedures are conducted accordingly to U.S. financial compliance standards. Consequently, Computershare, a global transfer agent specialized in sharing registry services and corporate trust, acted as the official custodian of the tokenized shares, maintaining the legal shareholder registry in parallel with the on-chain records. (Blockchain Guide, 2021; Alexa, 2025). It is evident how the issuing smart contract has the ability to be programmed not only to manage primary distributions like rent but also to enforce royalty fees automatically on any secondary sale. In practice, this means that if an investor token holder decides to sell stake on a secondary marketplace, a predefined percentage (e.g., 1–5%) will be automatically deducted and redirected via the smart contract to the original issuer or asset manager as a royalty. This royalty mechanism transforms tokenised real estate into a sort of income-generating asset not only at initial issuance and during operations, but also each time the ownership changes hands: for instance, if an investor sells a tokenised share of a real estate property on a compliant marketplace, the smart contract automatically deducts the royalty fee and transfers it to the issuer without requiring manual intervention since logic itself is programmed directly in the token's code (Hedera, 2025).

Exit Strategies

A key implementation introduced by tokenised real estate is the facilitation of more flexible and efficient exit strategies for investors that decide to step back from their investments with respect to traditional property markets. As a matter of fact, an exit strategy in investment refers to a planned approach that investors decide to adopt in order to withdraw their money from an asset or investment at a predefined point, either to realize profits or limit losses, based on their personal clear criteria or conditions (Hayes, 2023). Specifically, in the context of tokenised real estate, tokenisation enables investors to liquidate fractional property tokens that they are holding through compliant platforms, so obtaining a more flexible and efficient exit than traditional real estate investment, where usually it is required the sale of entire property (Le Gal, Nagayach & Swertvaeger, 2025). Concretely, investors have the ability to set specific exit conditions, like target returns, time horizons or liquidity needs, and then execute the trade on blockchain-enabled marketplaces or Alternative Trading Systems (ATS), where the transactions will be automatically executed and transparently recorded through the use of smart contracts (Soupel, 2025).

3.3 Project Guardian: Transforming Financial Markets through Tokenisation

Project Guardian is a major collaborative initiative launched by the Monetary Authority of Singapore (MAS) in May 2022, that aims at exploring the potentiality of the application of asset tokenisation and decentralised finance (DeFi) within regulated financial markets. Specifically, the initiative seeks to assess how tokenisation can improve market efficiency through the optimization of transparency, liquidity and accessibility while keeping regulatory safeguards. The project is structured into multiple phases and workstreams, where each of them focus on specific asset classes and technological innovations. It brings together over 24 major financial institutions, including J.P. Morgan, DBS Bank, SBI Digital, HSBC, Standard Chartered, BNY Mellon and Deutsche Bank, that decide to adhere in order to build an interoperable infrastructure and regulatory frameworks that, if implemented correctly, has the ability to eventually support a scalable ecosystem of tokenised financial products globally (Bogardi & Cai, 2024).

Authority and Development Framework

As mentioned before, the initiative is coordinated by the Monetary Authority of Singapore (MAS) in close partnership with international regulators such as the UK Financial Conduct Authority (FCA) and the Financial Services Agency of Japan (JFSA). MAS stands for Singapore's central bank and integrated financial regulator, authority which is responsible for overseeing the country's monetary policy, the financial institutions within the country and all the different capital markets. Concerning these duties, MAS plays a central role in fostering an efficient and forward-looking regulatory environment in order to support important experimentations with most promising emerging technologies implementation such as the tokenisation of financial assets. Regarding Project Guardian, the primary goal of MAS lies in the correct assessment of DLT to traditional financial assets such as bonds, funds, foreign exchange and real estate, while still conserving the protection of investors for their operations, keeping the market stability, and overseeing compliance framework. This project reflects concretely MAS's ambition to position Singapore as a global hub for digital asset innovation and aligns with broader regulatory goals that aim to enable responsible experimentation with blockchain-based financial infrastructure (MAS, 2024).

MAS's Project Guardian is essentially divided into key workstreams that involve Fixed Income and Foreign Exchange Tokenisation, Tokenised Fund Distribution, Decentralised Finance (DeFi) Protocols for Institutional Use, Interoperability and Settlement across Chains (MAS, 2024).

Phase One: Tokenised Wealth Management and Model Portfolios

This phase is specifically centered on the application of proof-of-concept (PoC) developed collaboratively by J.P. Morgan and Apollo. PoC is a small and controlled project used in order to test whether a certain idea or a specific technology actually may sort effectiveness in practice. It is important to highlight that it's never intended as a full and complete product, but its implementation is worth to declare that the system has value since it has the ability and the potential to solve a problem in the real world. In particular, concerning the case of Project Guardian, the PoC was used to test whether tokenised investments and the implementation of smart contracts could be automatized in order to manage investment portfolios automatically and efficiently through blockchain technology (J.P. Morgan, 2023).

In detail, the team created a tokenised investment fund using Singapore's Variable Capital Company (VCC) structure and simulated client contributions through tokenised fiat deposits. The VCC is a legal framework for investment funds introduced by the MAS and the Accounting and Corporate Regulatory Authority (ACRA) in January 2020. The idea was designed to increase Singapore competitiveness as a fund domicile through the combination between the operational flexibility of offshore fund structures, like those in the Cayman Islands or Luxembourg, and the robust regulatory oversight of Singapore. Specifically, these assets were issued and recorded on a permissioned blockchain network, in order to achieve a digitalized track and verification in real time of ownership rights and asset allocations. Through the implementation of smart contract logic, the platform was able to guarantee automated operations such as cash deployment, investor onboarding, eventual exit procedures and portfolio adjustments. At the same time, Apollo contributed through adding its expertise in product structuring phase and investment strategy while DBS served as the digital asset custodian, offering the wallet infrastructure in order to securely hold tokenised securities. In addition to this, the PoC also tested real-time portfolio construction trying to create a mix of tokenised fund units, various private assets and digital cash equivalents; it also had the duty of analyzing cross-chain interoperability through the examination of how effectively asset registries and ownership records could be tracked across multiple distributed ledgers (J.P. Morgan, 2023; MAS, 2024; Deutsche Bank, 2024).

Phase Two: Regulatory Integration and Technical Interoperability

In this phase, it is crucial to highlight how the emphasis shifts from theoretical pilots, observed during the previous step, to tangible frameworks with direct implications for future adoption in order to make a pivotal step toward institutional-grade deployment of tokenised financial instruments on a global scale. This stage of Project Guardian started in 2023, it is coordinated again by the MAS in collaboration with international key regulators such as the UK Financial Conduct Authority (FCA) and Japan's Financial Services Agency (JFSA) and it aimed to evaluate whether alternative asset classes, including private credit and tokenised real estate could be turned into tokenised fund units that are available to both retail and institutional investors across different jurisdictions.

One of the biggest achievements that the project wanted to obtain regards the development of a Tokenised Funds Interoperability Framework. This structure represents a set of standardized rules, protocols and technical guidelines, where the main goal is to ensure that tokenised investment funds have the chance of working together across different blockchain, financial institutions and multiple jurisdictions with the minimum interoperability issues (MAS, 2024). Concretely, the project focuses its attention on the testing of regulatory requirements such as KYC/AML compliance, settlement process and delivery of proficient financial reporting. The aim of the experiment lies in testing the execution of these operations through shared ledger technology in order to offer a potential improvement regarding potential friction and transparency issues. The initiative is adopted through a technical collaboration with important financial players such as BNY Mellon, Citi and Deutsche Bank, which help to demonstrate how possibly improve custodial and fund administration services and the way they could support tokenised fund structures better in a globally regulated framework (MAS, 2024).

Nowadays, Phase Two of Project Guardian is still on-going, and it serves as a strategic reference point for a present and future institutional adoption of blockchain-based finance. So far, its phased results are demonstrating a potential viable path toward full-scale digital transformation of asset management, where interoperability between different frameworks and programmable finance converge to define the next era of financial infrastructure.

3.4. Santander-Agrotoken Experiment: A new frontier for Agricultural Finance

In March 2022, Banco Santander Argentina and the agricultural technology firm (agritech) Agrotoken decided to launch a pioneering financial initiative aimed at transforming access to potential credit for farmers through the contribution of blockchain technology. Interestingly, this collaboration introduced the world's first initiative to offer loans secured by tokenised agricultural commodities, such as soybeans, corn and wheat. As a matter of fact, through the conversion of physical grain into digital tokens as collateral for guaranteeing the loans, the pilot aimed to enhance the traditionally rigid and slow-moving agricultural finance sector with a new technological framework. This strategic step came in the context of Santander's broader commitment to digital innovation and the initiative went supported by a USD 225 million investment in technology by the bank in Argentina (Santander, 2022).

Definition and objectives of Agrotokens

Agrotoken.io stands as the first grain tokenization platform and the gateway for agrobusiness into the world of the crypto economy (Agrotoken.io, 2022). As mentioned before, the company introduced a set of cryptoassets where the underlying assets are represented by real commodities: SOYA (soybean), CORA (corn) and WHEA (wheat). Each Agrotoken reflects one metric tonne of a specific grain that has been delivered and successfully tested through a Proof of Grain Reserve (PoGR) system: this mechanism aims to ensure a safe and transparent structure in order to validate the existence of the physical asset and its proper valuation. The main purpose behind the development of Agrotokens is to improve liquidity mechanism in the agricultural framework. Indeed, farmers are usually often asset-rich but cash-poor and this makes them face structural issues in obtaining convenient credit lines due to high collateral requirements and inefficiencies of lending systems. On the other hand, through the transformation of physical grain into a programmable digital asset, Agrotoken aims to create a chance for farmers to save, transact, and access capital markets easily, through their participation in broader decentralized finance ecosystems.

Agreement between Santander and Agrotoken

Banco Santander Argentina's interest in this collaboration is essentially driven by multiple components. The first one regards the important chance of innovating the structure of financial sector through a new adoption of digital solutions. As Argentina's largest private financial institution, counting more than 4 million customers, Santander has long expressed the desire to commit to blockchain innovation, especially in strategic sectors that represent a crucial resource to the national economy, such as agriculture framework (Santander Argentina, 2022). Concerning this, the collaboration with Agrotoken allowed the bank to innovate through the practical adoption of tokenised grain assets that serve as collateral for credit operations, unlocking new financial mechanisms that aim to modernize a segment of the economy where there is the presence of both asset-rich and liquidity-constrained individuals, which specifically constitute a major component of Argentina GDP (Ledger Insights, 2022). Regarding the initiative, Fernando Bautista, Head of Agribusiness at Santander Argentina, stated that their agreement with Agrotoken is the first real attempt concerning the implementation of blockchain and cryptoasset technology within the agricultural credit market, in order to finally unlock the full potential of farmer's business through a coherent connection with financial service platform (Santander Argentina, 2022; Ledger Insights, 2022).

Structured Breakdown of Agrotoken Tokenisation

The Agrotoken–Santander pilot project is structured around a robust and transparent end-to-end workflow that aims to transform physical agricultural assets into collateralised digital tokens in order to allow farmers to access credit more efficiently (Santander Argentina, 2022). The process is structured in different phases, where the first step regards grain delivery and verification, where farmers bring soy, corn, or wheat to certified wholesalers for demonstrating their ownership of physical underlying assets. Once this phase is completed, these grains are successfully authenticated through Agrotoken's Proof of Grain Reserve (PoGR) system, which generates a digital certificate that confirms the existence and quality of the commodity (Agrotoken.io, 2022). Once verified, Agrotoken issues tokens, SOYA, CORA, or WHEA, each representing one tonne of the respective grain, then these are indexed to real-time market prices using data from Matba Rofex, Argentina's principal agricultural futures exchange in order to ensure transparency and liquidity valuation (Ledger Insights, 2022). Finally, farmers have the possibility to apply for loans from Banco Santander Argentina, using the issued agrotokens as collateral: in case in which it is approved, the tokens are locked in escrow via smart contracts, which autonomously manage repayment terms and ensure contractual compliance. After, the loan can be repaid in fiat or additional agrotokens and the smart contract either releases or burns the tokens, according to the predetermined agreement. Through this streamlined model, it is possible to significantly reduce administrative burden and processing times with respect to the traditional agricultural lending process, which typically requires several days of manual validation (Santander Argentina, 2022).

Real Data and Impact of the Pilot

According to the data collected and Agrotoken and Santander's press statements, the pilot initially targeted a sample of 1,000 Argentine farmers in order to assess scalability and usability. During the following months from the launch date, the amount of underlying assets that have been tokenized increased over 30,000 tonnes of grain, demonstrating the rapid adoption of the experiment (Ledger Insights, 2022). Concerning the project, the tokens were issued across multiple blockchain platforms, including Ethereum, Polygon, and Algorand, being able to achieve a broader compatibility and access for individuals. The figures related to the experiment reflect not only the technological feasibility of the implementation but also demonstrate the market receptivity regarding it. As a matter of fact, this pilot has proven that tokenised assets can bring real-world value in a regulated financial setting and a potentially useful support loan origination, without the concrete need for physical collateral movement.

Despite the pilot is actually limited in scope, the 30,000+ tokenised tonnes of grain and the encouraging growth of the ecosystem of participants that have been considered in the experiment suggest the potential of scalability within the model. Concerning this, future expansion into other Latin-American countries and different types of agricultural commodities are already taken under consideration. In summary, the Agrotoken-Santander project is more than a potential technological innovation; in fact it marks a structural chapter regarding how value is created and measured in the agricultural market sector.

CONCLUSION

The tokenisation of financial assets represents a significant innovation in the evolution of financial markets through the implementation of decentralized technologies within the financial system. This thesis offered a comprehensive overview of how the entire process works in practice, highlighting the essential roles of DLT, blockchain frameworks and smart contracts in order to enhance security and transparency in the financial infrastructure.

Throughout the chapters, it is shown how tokenisation has the ability of improving efficiency of transactions, accessibility to more individuals and auditability across financial transactions via the automation of transaction processes that reduce the need of reliance on intermediaries and enhances the traceability of asset ownership. In this way, tokenisation offers to build a defined pathway toward more efficient and inclusive capital markets. Nevertheless, it is also clear how several technical, regulatory and operational challenges still do not allow its widespread adoption: particularly, these involve scalability limitations regarding the feasible amount of operations, interoperability concerns and fragmented legal frameworks across jurisdictions.

Furthermore, the thesis describes different real-world case studies that demonstrate the current value that tokenisation is already being implemented in specific areas of interest, giving special attention to real estate and banking sector, even though optimized only through a pilot program or early development stage. In particular, these examples are significant since they reveal both the potential and the limitations of current systems, highlighting the importance of a continuous cooperation between different sectors and the need of a more harmonized regulatory framework.

Concluding, even though tokenisation does not replace traditional financial structures, it shows a promising model that can facilitate and improve the financial system in the following years. Specifically, its successful implementation will depend not only on the continuous progress of its technological development but also on the establishment of a robust regulatory system and a massive industry standardization. As the global financial world evolves, tokenisation is expected to play a pivotal role in shaping the next generation of market infrastructure.

REFERENCES

Agrotoken. (n.d.). *Real value for a digital world*. Retrieved June 2025, from https://www.agrotoken.io

Agur, I., Villegas Bauer, G., Mancini-Griffoli, T., Martinez Peria, M. S., & Tan, B. (2025, January 29). *Tokenization and financial market inefficiencies* (Fintech Notes No. 2025/001). International Monetary Fund. https://doi.org/10.5089/9798400298905.063

Alexa, J. (2025, June 3). *Real estate tokenization: Feeding verified data to smart contracts for trust and transparency*. CoinMonks on Medium. https://medium.com/@jamesalexa0001/real-estate-tokenization-verified-data-smart-contracts-explained-ce189368f5e3

Antier Solutions. (2025). *The role of SPV structure in tokenization: A comprehensive guide*. https://www.antiersolutions.com/blogs/the-role-of-spv-structure-in-tokenization-a-comprehensive-guide/

Baker, W. (2025, June 27). *Best real estate crowdfunding sites for July 2025*. Investopedia. https://www.investopedia.com/the-best-real-estate-crowdfunding-sites-8761523

Banco Santander Argentina. (2022, March 7). *Santander and Agrotoken join forces to offer loans secured by cryptoassets* [Press release]. Santander. Retrieved June 2025, from https://www.santander.com/en/press-room/press-releases/2022/03/santander-and-agrotoken-join-forces-to-offer-loans-secured-by-cryptoassets?

Banerjee, A., Sevillano, J., Higginson, M., Rigo, D., & Spanz, G. (2024, June 20). *From ripples to waves: The transformational power of tokenizing assets*. McKinsey & Company. https://www.mckinsey.com/industries/financial-services/our-insights/from-ripples-to-waves-the-transformational-power-of-tokenizing-assets

Bank for International Settlements (BIS). (2024, October). *Tokenisation in the context of money and other assets: Concepts and implications for central banks* (CPMI Report No. D225). https://www.bis.org/cpmi/publ/d225.pdf

Bank for International Settlements (BIS). (2025, April). *Leveraging tokenisation for payments and financial transactions*. Bank for International Settlements. https://www.bis.org/publ/othp92.pdf

Bank for International Settlements, Innovation Hub. (2025, May 14). *Project Pine: Central bank open market operations with smart contracts* (Other Publication No. 95). https://www.bis.org/publ/othp95.htm

Bank for International Settlements. (2022, January 13). *BIS, SNB and SIX successfully test integration of wholesale CBDC settlement with commercial banks* [Press release]. https://www.bis.org/press/p220113.htm

Behnke, R. (2023, June 10). *What is Practical Byzantine Fault Tolerance in Blockchain?* Halborn. https://www.halborn.com/blog/post/what-is-practical-byzantine-fault-tolerance-in-blockchain

Bitbond & Bundesblock. (2022, December). *Current use cases for financial institutions*. https://www.bitbond.com/resources/current-use-cases-for-financial-institutions.pdf

Blockchain Guide. (2021). *Real estate tokenization*. https://www.blockchainguide.biz/tag/real-estate/

BNP Paribas. (2024, July 26). *First Eurozone sovereign digital bond issuance for the Republic of Slovenia issued and placed by BNP Paribas*. https://group.bnpparibas/en/press-release/first-eurozone-sovereign-digital-bond-issuance-for-the-republic-of-slovenia-issued-and-placed-by-bnp-paribas:contentReference[oaicite:5]{index=5}

Bogardi, E., & Cai, D. (2024, July 2). *MAS announces expansion industry collaboration to scale asset tokenisation for financial services*. Regulation Tomorrow. https://www.regulationtomorrow.com/asia/mas-announces-expansion-industry-collaboration-to-scale-asset-tokenisation-for-financial-services/

Brown, J. R. (n.d.). *What is a typical minimum investment in real estate?* Investopedia. Retrieved June 2025, from https://www.investopedia.com/articles/03/013103.asp?

Bulldog Law. (2025, April 22). *The rise of real estate tokenization: Legal considerations for investors and developers*. https://www.thebulldog.law/the-rise-of-real-estate-tokenization-legal-considerations-for-investors-and-developers

Business Wire. (2023, April 24). *Franklin Templeton Announces the Franklin OnChain U.S. Government Money Fund Surpasses $270 Million in Assets Under Management*. Retrieved June 2025, from https://www.businesswire.com/news/home/20230424005223/en/Franklin-Templeton-Announces-the-Franklin-OnChain-U.S.-Government-Money-Fund-Surpasses-%24270-Million-in-Assets-Under-Management/

Buterin, V. (2014). *Ethereum: A next-generation smart contract and decentralized application platform*. https://ethereum.org/content/whitepaper/whitepaper-pdf/Ethereum_Whitepaper_-_Buterin_2014.pdf

Carneiro, A. (2022, December 13). *What is R3 Corda and how it works*. BBChain. https://www.bbchain.com.br/en/blockchain-blog/what-is-r3-corda-and-how-it-works

Carroll, R. (2018, October 9). *In $18 million deal, nearly one-fifth of St. Regis Aspen sells through digital tokens*. The Aspen Times. https://www.aspentimes.com/trending/in-18-million-deal-nearly-one-fifth-of-st-regis-aspen-sells-through-digital-tokens/

Circle. (2025). *USDC | Regulated stablecoin for global opportunities*. Circle. https://www.circle.com/usdc

Coinbase. (2025). *What is a crypto whitelist?* Coinbase Learn. Retrieved June 2025, from https://www.coinbase.com/it/learn/tips-and-tutorials/what-is-a-crypto-whitelist?

Commodity Futures Trading Commission. (2020, December). *Digital assets primer*. CFTC LabCFTC. https://www.cftc.gov/media/5476/DigitalAssetsPrimer/download

Delmolino, K., Arnett, M., Kosba, A., Miller, A., & Shi, E. (2016). Step by step towards creating a safe smart contract: Lessons and insights from a cryptocurrency lab. In *Financial Cryptography and Data Security: FC 2016 International Workshops, BITCOIN, VOTING, and WAHC, Christ Church, Barbados, February 26, 2016, Revised Selected Papers 20* (pp. 79-94). Springer Berlin Heidelberg.

Deloitte & Baker McKenzie. (2022). *Real estate STO whitepaper: Chapter 2*. https://www2.deloitte.com/cn/en/pages/audit/articles/real-estate-sto-whitepaper-1st-paper-report.html

Deloitte Center for Financial Services. (2025, April 24). *Digital dividends: How tokenized real estate could revolutionize asset management*. Deloitte. https://www.deloitte.com/us/en/insights/industry/financial-services/financial-services-industry-predictions/2025/tokenized-real-estate.html

Deloitte. (2024.). *Tokenization in financial services*. Deloitte. https://www.deloitte.com/us/en/industries/financial-services/articles/tokenization-in-financial-services.html

Derby, M. S., & Jones, M. (2025, May 14). Central-bank project shows monetary policy still viable in tokenized system. *Reuters*. https://www.reuters.com/business/finance/central-bank-project-shows-monetary-policy-still-viable-tokenized-system-2025-05-14/

Deutsche Bank. (2024, May 14). *Deutsche Bank joins Project Guardian to explore asset tokenization applications*. https://www.db.com/news/detail/20240514-deutsche-bank-joins-project-guardian-to-explore-asset-tokenization-applications

Deutsche Bank. (2025, January 29). *Evonik and Deutsche Bank issue green bond using Clearstream's D7*. https://corporates.db.com/more/latest-news/evonik-and-deutsche-bank-partner-to-issue-electronic-securities-via-clearstreams-digital-platform/

Disparte, D., & Liao, G. (2024, October). *Tokenization of financial assets and the paradox of programmability*. World Economic Forum. https://www.weforum.org/stories/2024/10/tokenization-financial-assets-crypto-programmable-paradox/

Ekberg, J., de Lima, L., Ho, M., Hung, T., Desouza, K., Pelupessy, N. C., Ng, P. K., Low, Y. S., Mallela, N., Sharma, N., Lobban, T., Zaltsman, N., Beale, J., & Argibay, P. (2022, November). *Institutional DeFi*. Oliver Wyman Forum. https://www.oliverwymanforum.com/future-of-money/2022/Nov/institutional-defi.html

Ethereum Foundation. (2025, February 12). *Introduction to smart contracts*. Ethereum.org. https://ethereum.org/en/developers/docs/smart-contracts/

European Central Bank. (2024, October 7). *Towards a digital capital markets union: The transformative potential of tokenisation and DLT in capital markets* [Keynote speech by ECB Executive Board member Piero Cipollone]. European Central Bank. Retrieved June 2025, from https://www.ecb.europa.eu/press/key/date/2024/html/ecb.sp241007~cc903db51d.en.html afme.eu+3ecb.europa.eu+3hkifoa.com+3

Fariha, F. (2023, November 14). *What is R3 Corda and how does R3 Corda work?* Core Devs Ltd. https://coredevsltd.com/articles/r3-corda/

FasterCapital. (2025). *Structuring token offerings with SPVs*. Retrieved June 2025, from https://fastercapital.com/topics/structuring-token-offerings-with-spvs.html

FCIQ. (2025, January 30). *Real-estate tokenization platforms: How digital shares are revolutionizing property investment*. FCIQ. https://www.fciq.ca/blockchain-and-cryptocurrency/real-estate-tokenization-platforms-how-digital-shares-are-revolutionizing-property-investment/

Federal Financial Supervisory Authority (BaFin). (2021). *Annual report 2021*. https://www.bafin.de/SharedDocs/Downloads/EN/Jahresbericht/dl_jb_2021_en.html

Federal Reserve Bank of Minneapolis. (1998, December 1). *What does "mixed-use development" mean?* Federal Reserve Bank of Minneapolis. https://www.minneapolisfed.org/article/1998/what-does-mixeduse-development-mean

Federal Reserve Bank of New York. (2025). *Project Pine: central bank open-market operations with tokenized assets*. New York Innovation Center. https://www.newyorkfed.org/aboutthefed/nyic/project-pine

Federal Reserve Board**.** (2023, April 3). *Tokenized assets on public blockchains: How transparent is the blockchain?* Federal Reserve FEDS Note. Retrieved June 2025, from https://www.federalreserve.gov/econres/notes/feds-notes/tokenized-assets-on-public-blockchains-how-transparent-is-the-blockchain-20240403.htm

Financial Stability Board. (2024, October 22). *The financial stability implications of tokenisation* (Report No. P221024-2). Financial Stability Board. https://www.fsb.org/uploads/P221024-2.pdf

GeeksforGeeks. (2023, April 24). *What is consortium blockchain?* GeeksforGeeks. https://www.geeksforgeeks.org/what-is-consortium-blockchain/

GeeksforGeeks. (2024, June 11). *Blockchain in brief*. GeeksforGeeks. https://www.geeksforgeeks.org/ethical-hacking/blockchain-in-brief/

GeeksforGeeks. (2025, April 21). *Public Blockchain*. GeeksforGeeks. https://www.geeksforgeeks.org/ethical-hacking/public-blockchain/

Global Financial Markets Association. (2023, May). *The impact of distributed ledger technology in global capital markets*. https://www.gfma.org/policies-resources/gfma-publishes-report-on-impact-of-dlt-in-global-capital-markets/

GlobeNewswire. (2025, January 27). *Real estate market size to hit USD 7.84 trillion by 2033*. https://www.globenewswire.com/news-release/2025/01/27/3015707/0/en/Real-Estate-Market-Size-to-Hit-USD-7-84-trillion-by-2033-Straits-Research.html

Hayes, A. (2023, March 20). *Exit strategy definition for an investment or Business*. Investopedia. https://www.investopedia.com/terms/e/exitstrategy.asp?

Hedera. (2025). *Real estate tokenization: Transforming property investment*. Hedera. https://hedera.com/learning/tokens/real-estate-tokenization

Imperva. (2025). Tokenization. *Imperva*. https://www.imperva.com/learn/data-security/tokenization/

J.P. Morgan. (2023). *Project Guardian*. Kinexys by J.P. Morgan. https://www.jpmorgan.com/kinexys/project-guardian

KfW. (2025, April 10). *KfW participates in digital Pfandbrief on SWIAT platform*. https://www.kfw.de/About-KfW/Newsroom/Latest-News/Pressemitteilungen-Details_848192.html

Kumar, S., Suresh, R., Liu, D., Kronfellner, B., & Kaul, A. (2022, September 12). *Relevance of on-chain asset tokenization in 'crypto winter'*. Boston Consulting Group. https://web-assets.bcg.com/1e/a2/5b5f2b7e42dfad2cb3113a291222/on-chain-asset-tokenization.pdf

LCX. (2024). *The transformative role of smart contracts in asset tokenization*. LCX.https://www.lcx.com/the-transformative-role-of-smart-contracts-in-asset-tokenization/?

Le Gal, L., Nagayach, M., & Swertvaeger, R. (2025, February 24). *Real estate tokenization: A new era for property investment and Luxembourg's strategic role*. EY Luxembourg. https://www.ey.com/en_lu/insights/real-estate-hospitality-construction/real-estate-tokenization-a-new-era-for-property-investment-and-luxembourg-s-strategic-role

Ledger Academy. (2023, September 8). *Public blockchain meaning*. Ledger. https://www.ledger.com/academy/glossary/public-blockchain

Ledger Insights. (2022, March 8). *Santander provides crypto loans against Agrotoken tokenized commodities*. Ledger Insights. https://www.ledgerinsights.com/santander-provides-crypto-loans-against-agrotoken-tokenized-commodities-blockchain/

Lutkevich, B. (2023, February 7). *Tokenization*. SearchSecurity. https://www.techtarget.com/searchsecurity/definition/tokenization

Martin, E. J. (2022). *What is commercial real estate?* Bankrate. Retrieved June 2025, from https://www.bankrate.com/real-estate/commercial-real-estate-loan/?

McAndrew, C. (2025). *The art market 2025: Art market insights report*. UBS. https://www.ubs.com/global/en/our-firm/art/art-market-insights/download-market-report-2025.html

McKinsey & Company. (2023, January 3). *What is proof of stake?* McKinsey & Company. https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-proof-of-stake?

McKinsey & Company. (2024, July 25). *What is tokenization?* https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-tokenization#/

Monetary Authority of Singapore (MAS). (2024). *Project Guardian*. https://www.mas.gov.sg/schemes-and-initiatives/project-guardian

Mudrex. (2023, March 28). *What is a consortium blockchain? Features and use cases*. Mudrex Learn. https://mudrex.com/learn/what-is-consortium-blockchain/

MuleSoft. (2025). *What is a single source of truth (SSOT)*. Retrieved June 2025, from https://www.mulesoft.com/resources/esb/what-is-single-source-of-truth-ssot?

Nakamoto, S. (2008, October 31). *Bitcoin: A peer-to-peer electronic cash system*. https://www.bitcoin.org/bitcoin.pdf bitcoin.org+10

National Institute of Standards and Technology (NIST). (2025, May 27). *Glossary*. NIST Computer Security Resource Center. https://csrc.nist.gov/glossary

National Institute of Standards and Technology. (n.d.). *Cryptographic hash function*. NIST Computer Security Resource Center Glossary. Retrieved June 2025, from https://csrc.nist.gov/glossary/term/cryptographic_hash_function

Notabene. (2024). *Crypto Travel Rule 101: KYC & the crypto travel rule*. Notabene. https://notabene.id/crypto-travel-rule-101/kyc-crypto

Organisation for Economic Co-operation and Development (OECD). (2018, April). *OECD Blockchain Primer*. OECD Blockchain Policy Forum. https://cdn.gihub.org/umbraco/media/2431/oecd-blockchain-primer.pdf

Organisation for Economic Co-operation and Development (OECD). (2025). *Finance and investment*. OECD. https://www.oecd.org/en/topics/finance-and-investment.html

Organisation for Economic Co-operation and Development (OECD). (2025, January). *Tokenisation of assets and distributed ledger technologies in financial markets: Potential impediments to market development and policy implications* (OECD Business and Finance Policy Papers, No. 75). OECD Publishing. https://doi.org/10.1787/40e7f217-en

Organisation for Economic Co-operation and Development (OECD). (2020, March 27). *The tokenisation of assets and potential implications for financial markets* (OECD Blockchain Policy Series). OECD Publishing. https://doi.org/10.1787/83493d34-en

Oyelabs. (2024). *Real estate tokenization – A complete guide for beginners.* Retrieved June 2025, from https://oyelabs.com/complete-guide-to-real-estate-tokenization/

Phemex Academy. (2021, October 20). *What is Quorum: A closer look at an enterprise blockchain giant*. Phemex Academy. https://phemex.com/academy/what-is-quorum-jp-morgan?

Rańda, D. (2025, June 25). *What are the types of blockchain technology? Explaining and comparing different blockchain types*. CrustLab. https://crustlab.com/blog/types-of-blockchain-technology-a-complete-overview/

RealT. (n.d.). *Real estate security token platform*. Retrieved June 2025, from https://realt.co/?

Rodrigues, F. (2025, May 14). *JPMorgan's Kinexys connects with public blockchain on Ondo Chain testnet debut*. CoinDesk. https://www.coindesk.com/business/2025/05/14/jpmorgans-kinexys-connects-with-public-blockchain-on-ondo-chain-testnet-debut

Rynes, Z. (2023, February 18). *Tokenized real-world assets (RWAs): Scaling onchain finance to a global level*. Chainlink Blog. https://blog.chain.link/tokenized-real-world-assets/

Santander. (2022, March 7). *Santander and Agrotoken join forces to offer loans secured by cryptoassets*. Santander. https://www.santander.com/en/press-room/press-releases/2022/03/santander-and-agrotoken-join-forces-to-offer-loans-secured-by-cryptoassets

Securities and Exchange Commission (SEC). (2024, June 21). *General solicitation — Rule 506(c)*. https://www.sec.gov/resources-small-businesses/exempt-offerings/general-solicitation-rule-506c

Security Token Market. (2025, June 27). *AspenCoin (St. Regis) Token - ASPD Price*. https://stomarket.com/sto/aspencoin-st-regis-aspd

Seth, S. (2024, November 2). *Public, private, and permissioned blockchains compared*. Investopedia. https://www.investopedia.com/news/public-private-permissioned-blockchains-compared/

Shafii, K. (2023, November 20). *Blockchain vs. distributed ledger technology (DLT): Understanding the differences*. Consensus. https://www.consensus.com/blog/blockchain-vs-dlt/

Sharma, T. K. (2024, June 6). *Types of blockchains explained: Public vs private vs consortium*. Blockchain Council. https://www.blockchain-council.org/blockchain/types-of-blockchains-explained-public-vs-private-vs-consortium/

Singh, D. (2024, November 11). *Smart contracts in real estate tokenization: Revolutionizing property transactions*. Debut Infotech. https://www.debutinfotech.com/blog/smart-contracts-in-real-estate-tokenization

Singh, D. (2025, February 27). What is public blockchain and how does it work? *Debut Infotech*. https://www.debutinfotech.com/blog/what-is-public-blockchain?

Solidity Foundation. (2025). *Contracts: Function modifiers*. In *Solidity Documentation (version 0.8.31)*. Retrieved from https://docs.soliditylang.org/en/latest/contracts.html#function-modifiers

Solidity Foundation. (2025, May 7). *Solidity v0.8.30 documentation*. https://docs.soliditylang.org/en/v0.8.30/

Soupel, V. (2025, May 8). *Real estate tokenization to redefine investing in real estate.but regulators may curb market growth.* ScienceSoft. https://www.scnsoft.com/finance/tokenization-to-redefine-investing-in-real-estate

Squire Patton Boggs. (2021, June). *German law on the introduction of electronic securities*. Squire Patton Boggs. https://www.squirepattonboggs.com/-/media/files/insights/publications/2021/06/german-law-on-the-introduction-of-electronic-securities/germanlawontheintroductionofelectronicsecurities.pdf

Stellar Development Foundation. (2022, November 10). *Not all data is equal: How Soroban is solving state bloat with state expiration*. Stellar Developer Blog. Retrieved June 2025, from https://stellar.org/blog/developers/not-all-data-is-equal-how-soroban-is-solving-state-bloat-with-state-expiration?

STM Market. (n.d.). *AspenCoin (ASPD) token overview and market data*. Retrieved June 30, 2025, from https://stomarket.com/sto/aspencoin-st-regis-aspd?

Susnjara, S., & Smalley, I. (2025). *Blockchain*. IBM Think. https://www.ibm.com/think/topics/blockchain

Syndicately. (2023, February 10). *A simple guide to setting up your SPV*. https://www.syndicately.com/blog/a-simple-guide-to-setting-up-your-spv/

Synodus. (2024). *The future of asset tokenization: Here's what you can expect*. Retrieved June 2025, from https://synodus.com/blog/blockchain/future-of-asset-tokenization/

Synodus. (2024, April 25). *14 smart contracts use cases & real examples across industries*. Synodus. https://synodus.com/blog/blockchain/smart-contracts-use-cases/

Tamplin, T. (2023, September 7). *DLT vs blockchain: Tanım, avantajlar, dezavantajlar ve farklar*. Finance Strategists. https://www.financestrategists.com/wealth-management/blockchain/dlt-vs-blockchain/

Tezos. (2025). *Michelson reference* [Documentation]. https://tezos.gitlab.io/michelson-reference/

U.S. Securities and Exchange Commission. (2019). *Framework for "investment contract" analysis of digital assets*. https://www.sec.gov/files/dlt-framework.pdf

UBS. (2022, November 3). *UBS and SDX issue world's first fully digital CHF bond using blockchain technology*. UBS Media Release. Retrieved June 2025, from https://www.ubs.com/global/en/media/display-page-ndp/en-20221103-digital-bond.html?

Utimaco. (2024). *What are the types of nodes in blockchain?* Utimaco. https://utimaco.com/service/knowledge-base/blockchain/what-are-the-types-of-nodes-in-blockchain

Wilson, B. (2023, October 11). *Reimagining the capital stack for tokenized real estate*. Upside. https://www.upside.gg/the-ledger/reimagining-the-capital-stack-for-tokenized-real-estate

Wood, G. (2025). *Ethereum: A secure decentralised generalised transaction ledger* Ethereum Foundation. https://ethereum.github.io/yellowpaper/paper.pdf

World Bank. (2020, May). *Distributed Ledger Technology and Secured Transactions* (Guidance note). World Bank. https://documents1.worldbank.org/curated/en/541741588053800973/pdf/Distributed-Ledger-Technology-and-Secured-Transactions-Framework.pdf

World Economic Forum. (2025, May 21). *Asset tokenization in financial markets: The next generation of value exchange*. https://www.weforum.org/publications/asset-tokenization-in-financial-markets-the-next-generation-of-value-exchange/

Yaga, D. J., Mell, P. M., Roby, N., & Scarfone, K. (2018, October 3). *Blockchain technology overview* (NIST Interagency/Internal Report No. 8202). National Institute of Standards and Technology. https://doi.org/10.6028/NIST.IR.8202