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A blockchain framework for increased trust in green bonds issuance

Vangelis Malamas · Thomas K. Dasaklis · Veni Arakelian · Gregory Chondrokoukis

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Abstract Bonds issuance is a highly technical and complicated process, entailing mutually untrusted stakeholders with sometimes conflicting objectives. Currently, the global bond market is faced with several pain points when it comes to bond issuance, like disparate regulatory frameworks, limited traceability and auditability, settlement failures and inefficient issuance processes. Blockchain technology is capable of addressing some of the issues mentioned above. In this paper, we propose a blockchain-enabled green bond issuance architecture. In particular, we develop an adaptable and efficient system that reduces the intermediary costs and offers compliance, scalability, confidentiality, and security. The blockchain-enabled system also acts as a transparent yet fully controllable decentralized authority where the funds of qualified, environmentally friendly projects could be traced. Our proposed architecture

Vangelis Malamas
Department of Informatics
University of Piraeus, Piraeus (Greece)
E-mail: bagmalamas@unipi.gr

Thomas K. Dasaklis
Department of Informatics
University of Piraeus, Piraeus (Greece)
E-mail: dasaklis@unipi.gr

Veni Arakelian
Senior Economist at Economic Analysis and Investment Strategy, Piraeus Bank (Greece)
E-mail: veniarakelian@yahoo.com (preferred), arakelianv@piraeusbank.gr

Gregory Chondrokoukis
Department of Industrial Management and Technology
University of Piraeus, Piraeus (Greece)
E-mail: gregory@unipi.gr

considers the various aspects and the complexity of the bond issuance procedures and the special requirements of green bonds. The architecture is based on a five-step model from green bond initialization to archiving. To adjust the processes of bond issuance to a blockchain-enabled model, we use digital tokens based on the ERC-20 token standard. Within the smart contracts developed, we use various functions to handle the prerequisites of validators and regulators' approval based on the documentation presented and the parameters of rate and maturity requested by the issuer. We use a separate smart contract to implemented forensic services. The overall system also considers various regulatory compliance instruments and enhances access of regulatory bodies to issuance records. We believe that the proposed architecture could be of significant value to researchers and practitioners from the financial domain.

Keywords Green bonds · blockchain · bond issuance · blockchain tokens

1 Introduction

According to the International Capital Market Association (ICMA), the overall size of the global bond markets (as of August 2020) in terms of USD equivalent notional outstanding is approximately \$128.3tn[1]. Bonds can be classified according to the market of issuance, either as on-shore (national) or off-shore (Eurobond market). The on-shore markets can be further broken down into two markets: a) domestic, where the bond is an obligation of a domestic issuer that is offered in the domestic market[2], and, b) foreign, where the bond issued by a foreign issuer[3]. Eurobonds are issued and traded internationally and are often not denominated in a currency native to the country of the issuer (see for example, Iannotta et al. (2014)). Contrary to the foreign bonds, they usually do not have registration requirements and the possession is evidence of ownership. Contrary to the conventional unsecured loan stocks of the same issuer, the Eurobonds' yield will be slightly lower. Enabling issuers to add novel features, it gives them the potential to appeal to different investors.

During the last decade, green or climate bonds have gained significant momentum. Although green bonds represent only 2% of total bonds issuance worldwide, they are still considered a critical financial instrument since they facilitate sustainable investing for a multitude of institutional investors Foster (2019). In particular, green bonds are an important financial tool for funding environmental projects through a low-carbon financing approach Reboredo (2018). A green bond is a fixed-income instrument specifically designed to finance projects with positive environmental and/or climate benefits (where proceeds are directed to green assets). Projects with a positive environmental and/or climate benefits range from building wind and solar farms to developing sea walls in cities threatened by rising sea levels. Similar to any other

[1] https://www.icmagroup.org/Regulatory-Policy-and-Market-Practice/Secondary-Markets/bond-market-size/

[2] E.g., a bond issued and traded in Italy by an Italian issuer is a domestic bond

[3] E.g., a bond issued and traded in the US by a German issuer

bond, green bonds are financial securities in which the bond issuer sells a contract promising repayment and a specified rate of interest Sanderson (2018). Green bonds are seen as a critical instrument for our transition to low-carbon economies Sartzetakis (2020), particularly for achieving the 17 Sustainable Development Goals (SDG) set by the United Nations by 2030. They follow the Green Bond Principles stated by the ICMA, and the proceeds from the issuance of which are to be used for the pre-specified types of projects International Capital Market Association (2018). Yearly proceeds allocation trends reveal increasing disbursements to renewable energy, clean water, low-carbon transportation, and other Paris Agreement and SDG-related investment categories Tolliver et al. (2019). According to Climate Bonds Initiative (2020), the cumulative market size of green bonds issuance from inception (2007) until the end of 2019 totaled to USD754bn.

Green bonds provide investors not only with the benefit of knowing that the proceeds of their investment are being used in an environmentally positive way but also with significant financial gains. According to recent studies, green bonds issuance is beneficial to a firm's existing shareholders Tang and Zhang (2020). Other studies suggest that green bonds outperform, from a financial point of view, conventional bonds. In particular, the financial gain is larger for corporate issuers, and it persists in the secondary market Gianfrate and Peri (2019). For scaling up the green bonds market, however, an increase in investors' green awareness and governmental tax-based incentives will be necessary Agliardi and Agliardi (2019).

1.1 Blockchain technology and the financial sector

Blockchain technology, a foundational technology of the Fourth Industrial Revolution, is expected to play a crucial role in various domains Casino et al. (2019). Blockchain is the technology that underpins all cryptocurrencies and was first introduced as the underlying technology of the Bitcoin digital currency. In general, a blockchain may be considered an append-only distributed database, specifically referred to as a ledger where records of all transactions occurring in a peer-to-peer network may be stored. All records are kept in a sequence of blocks where every block contains a list of transactions, a hash of all the transactions, and the hash of the transactions of the previous block. All transactions are strictly documented and timestamped inside blocks, and these blocks are tightly linked to each other (using cryptographic hashes). Once transactions are recorded into a blockchain, it becomes extremely difficult to change or alter them, thus making blockchains practically immutable data records. Due to the distributed nature of blockchain, all peers of the network own a copy of the ledger.

For achieving the necessary agreement on the state of the network (and particularly which transactions are legitimate and should be added to the blockchain), the nodes use fault-tolerant mechanisms, also known as consensus mechanisms. These mechanisms provide a non-partisan means of ensuring that only the true state of the network is maintained, and they further safeguard the validity of transactions taking place within the network. Various consensus mechanisms exist; however, *Proof of Work* and *Proof of Stake* are the most common and extensively used consensus mechanisms across a plethora of real-life blockchain applications. The above-mentioned mechanisms present different characteristics concerning computation time, speed, security and scalability. Depending on the nodes' permission rights, three types of blockchain networks exist; public, permissioned and federated networks.

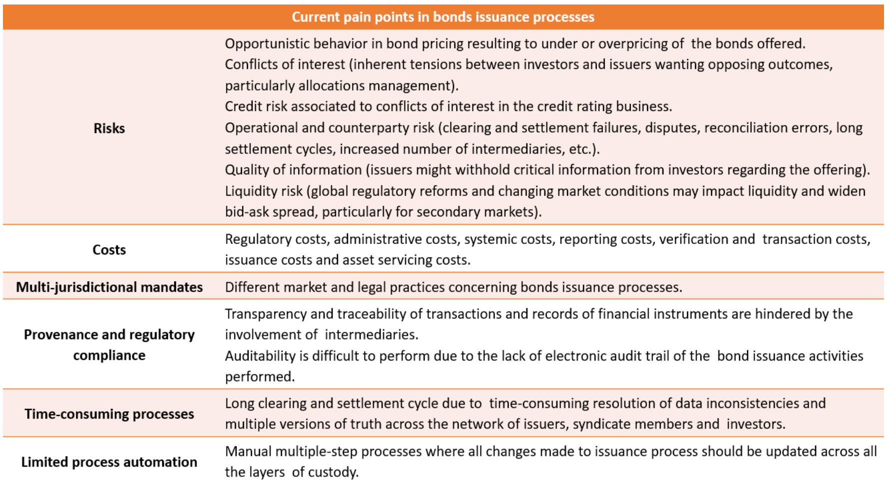
Within a blockchain network, users can deploy pieces of software known as smart contracts. Smart contracts are essentially computer code running on top of a blockchain network and can be thought of as a digitized version of traditional contracts. A smart contract contains a set of rules/conditions in the form of a self-enforcing agreement under which the parties to that smart contract agree. The code of the smart contract is automatically executed once the predetermined rules/conditions are met. Smart contracts offer additional functionalities in blockchain networks since they foster transaction credibility, automation and efficiency Casino et al. (2019).

Financial firms and regulators have been experimenting with blockchain technology for several years, particularly in an attempt to streamline banking and lending services, bring down operational costs and reduce counterparty risk and settlement times World Economic Forum (2015). Well-know initiatives include the Corda ecosystem (a distributed ledger platform designed to record, manage and synchronise financial agreements between regulated financial institutions) as well as various blockchain-enabled security issuance initiatives. For example, in partnership with Commonwealth Bank of Australia, the World Bank issued the first "Bond" created, allocated, transferred, and managed throughout its life-cycle using blockchain technology[4]. In early 2019, Santander issued the first blockchain-enabled green bond Santander (2019). It is expected that the fintech-related blockchain market size will grow from USD 231.63 million in 2017 to USD 6700.63 million by 2023, at a compound annual growth rate of 75.2% during the forecast period (Market Research Future, 2020).

1.2 Motivation and contribution

Bonds issuance is a highly technical and complicated process, entailing mutually untrusted stakeholders with sometimes conflicting objectives Van der Wansem et al. (2019). Currently, the global bond market is faced with several pain points when it comes to bonds issuance. For instance, although capital raising processes have common characteristics across different jurisdictions, variations are found in both market practice and relevant regulatory frameworks governing the bonds issuance processes International Organization of Securities Commissions (2019). Limited traceability and auditability also present

[4] https://www.worldbank.org/en/news/press-release/2018/08/09/world-bank-mandates-commonwealth-bank-of-australia-for-worlds-first-blockchain-bond



Current pain points in bonds issuance processes	
Risks	Opportunistic behavior in bond pricing resulting to under or overpricing of the bonds offered. Conflicts of interest (inherent tensions between investors and issuers wanting opposing outcomes, particularly allocations management). Credit risk associated to conflicts of interest in the credit rating business. Operational and counterparty risk (clearing and settlement failures, disputes, reconciliation errors, long settlement cycles, increased number of intermediaries, etc.). Quality of information (issuers might withhold critical information from investors regarding the offering). Liquidity risk (global regulatory reforms and changing market conditions may impact liquidity and widen bid-ask spread, particularly for secondary markets).
Costs	Regulatory costs, administrative costs, systemic costs, reporting costs, verification and transaction costs, issuance costs and asset servicing costs.
Multi-jurisdictional mandates	Different market and legal practices concerning bonds issuance processes.
Provenance and regulatory compliance	Transparency and traceability of transactions and records of financial instruments are hindered by the involvement of intermediaries. Auditability is difficult to perform due to the lack of electronic audit trail of the bond issuance activities performed.
Time-consuming processes	Long clearing and settlement cycle due to time-consuming resolution of data inconsistencies and multiple versions of truth across the network of issuers, syndicate members and investors.
Limited process automation	Manual multiple-step processes where all changes made to issuance process should be updated across all the layers of custody.

Fig. 1: Current pain points in bonds issuance processes

significant pain points in the overall bonds issuance process. Due to the increased number of intermediaries (issuing agent, paying agent, 'Bill & Deliver' agent), which centrally keep records of financial instruments, it is extremely difficult to trace a person's entitlement to a financial instrument. Bond issuance costs (like regulatory, certification, transactions, reporting, verification, systemic, settlement and back-office costs) further limit bond returns. Settlement failures, disputes, conflicts of interest (allocation conflicts) and reconciliation errors are just a few among the various operational and counterparty risks associated with bonds issuance International Organization of Securities Commissions (2019). Finally, current bonds issuance practices rely on inefficient, manual, multiple-step processes that, apart from time-consuming, are also prone to errors Shaikh and Zaka (2019). In Fig. 1, we present the overall challenges and issues related to the traditional bonds issuance process.

It is worth noting that green bonds issuance presents additional challenges. For example, lack of common standards may increase confusion and green bonds issuers are faced with reputational risk if the green integrity of the bond or bond's green credentials are questioned Kaminker et al. (2017). Another key-challenge facing green bonds issuance is building credibility in markets where trust is low, particularly for reporting the investment's environmental benefits HSBC and Sustainable Digital Finance Alliance (2019). In addition, many potential issuers have limited knowledge of the green bond issuance process Climate Bonds Initiative and International Institute for Sustainable Development (2016).

Blockchain technology is capable of addressing some of the issues mentioned above. To this end, we propose a blockchain-enabled green bond issuance architecture. Our main goal is to develop an adaptable and efficient system that reduces the intermediary costs and offers compliance, scalability, confidentiality, and security. The blockchain-enabled system also acts as a transparent yet fully controllable decentralized authority where the funds of qualified, environmentally friendly projects could be traced. Our proposed architecture considers the various aspects and the complexity of the bond issuance procedures along with the special requirements of green bonds. The architecture is based on a five-step model from green bond initialization to archiving. To adjust the processes of bond issuance to a blockchain-enabled model, we need to tokenize the bonds. The digital token is created through a smart contract with a specific standard (in our case ERC-20). Within the smart contracts developed, we use various functions to handle the prerequisites of validators and regulators' approval based on the documentation presented and the parameters of rate and maturity requested by the issuer. We use a separate smart contract to implemented forensic services.

1.3 Paper structure

The remainder of the paper is organized as follows. In Section 2 we present an overview of the available blockchain-enabled security issuance frameworks pertaining to both the scientific and grey literature. In Section 3 we describe the proposed blockchain-based green bonds issuance architecture and its functional characteristics. In Section 4 we detail our proof of concept implementation along with the experimentation design. In Section 5 we discuss the various security and performance characteristics of the proposed architecture and we outline critical prerequisites for wider adoption of blockchain technology in the financial sector. The paper ends with some concluding remarks.

2 Literature review

Arguably, the usage of blockchain technology in securities markets is still in its infancy. However, various key-players and policymakers within the financial sector have started engaging in a race to harvest the potential benefits of blockchain technology in securities issuance Seretakis (2019). The application of blockchain technology on green bonds issuance can be split in three broad areas HSBC and Sustainable Digital Finance Alliance (2019): a) Structuring, issuance and distribution b) Transfer of ownership, payment and settlement and c) Benchmarking and reporting. Security issuance practices require many records of information (like records of holdings of financial instruments, terms of contracts and payment details), which are currently managed by trusted third parties in a rather centralised manner. Blockchain technology offers an alternative way to manage securities issuance records and certificates by completely digitizing the overall process Capgemini (2016). According to recent studies the efficiency gains of blockchain-enabled bond issuance are at the magnitude of 10X when compared to non-blockchain bond issuance approaches. The largest efficiency gains (measured in terms of money saved) would come via lowered costs for reporting, brokerage, and sales as well as structuring, price setting and risk rating HSBC and Sustainable Digital Finance Alliance (2019).

Other benefits from blockchain usage in security issuance include greater transparency and faster clearing and settlement, enhanced recording and tracking of ownership of the securities, fewer intermediaries, and easier collection and sharing of data for supervisory purposes Seretakis (2019). Blockchain technology could also facilitate the implementation of a unique reference system in securities markets by incorporating unique security identifiers into the trade lifecycle processes Capgemini (2016). Special focus has also been paid in corporate bonds issuance. Market participants are exploring issuance and trading of corporate bonds using blockchain technology, particularly for automating the calculation and payment of coupons and redemption Workie and Jain (2017). The usage of blockchain technology has been recently proposed in the case of "asset-backed" borrowing schemes like Sukuk Shaikh and Zaka (2019). However, since blockchain is a relatively new technology, various legal issues remain unaddressed when using blockchain in securities issuance Cohen et al. (2018). In Ryan and Donohue (2017), the authors provide guidance to corporate lawyers faced with giving a legal opinion regarding issuance and sale of securities on a blockchain.

Blockchain technology is considered a game-changer in securities issuance from a sustainability point of view as well HSBC and Sustainable Digital Finance Alliance (2019). During the last couple of years, blockchain technology has been considered the catalyst for driving the transition to a low carbon, sustainable and climate-resilient economy, thus achieving the Paris Agreement's goals Foster (2019). In particular, blockchain technology has the potential to help scale climate action and with its traceability-by-design features to enhance impact validation of green bonds issuance, thus, unlocking greater funding opportunities in green projects Climate Bonds Initiative and International Institute for Sustainable Development (2016). For example, the Green Assets Wallet, an independent and trust-by-design built platform for green securities, offers issuers the ability to transparently and directly communicate their green bond offerings and achievements in an attractive format for investors[5]. Other interesting initiatives include the so-called "forest bonds" representing financial instruments aimed at stopping deforestation Sanderson (2018). Blockchain technology is expected to simplify green bond issuance processes, by improving traceability of the overall issuance processes and providing verification and auditability of relevant requirements Poberezhna (2018). Also, blockchain technology is expected to facilitate the compliance and enforcement of various climate-related laws and financial regulatory frameworks in a low-cost and high-speed manner by the various stakeholders Zhang et al. (2018).

[5] https://greenassetswallet.org/

3 The proposed blockchain-enabled green bond issuance architecture

The bond trading market's main characteristics include shared repositories among the various untrusting participants, significant costs added by the central intermediaries, and a relatively time-consuming procedure. Furthermore, the need for processing transparency and bond chain of custody, especially in the use-case of green bonds, push the need for a decentralized solution.

To overcome the classical model's limitations, we propose a blockchain-enabled green bond issuance framework. The proposed model's goal is to develop an adaptable and efficient system that reduces the intermediary costs severally and offers compliance, scalability, confidentiality, and security. Besides, the system acts as a transparent yet fully controllable decentralized authority.

Our proposed architecture considers the various aspects and the complexity of the bond issuance procedures along with the special requirements of green bonds.

In this section, we present our architecture structure and key players who participate in the system and the processes taking place. Note that in our scheme, we have taken into account the compliance to UCC section 8-401(a), which differentiates from other blockchain applications in anonymity. According to UCC, the issuer of a blockchain security must know the owner's identity of that blockchain security. Also, to allow the transferor to be identified to the transferee so that the transferee can exercise rights in respect of the warranties under UCC section 8-108(b), the transferors' identity blockchain securities cannot be anonymous, Ryan and Donohue (2017). Therefore, a private blockchain structure was selected, allowing transparency between the participants while maintaining anonymity outside the ecosystem.

3.1 Requirements and key-players

The bond exchange ecosystem involves various participants who often have different or even contradicting goals; thus the system must enforce trust among them. For this reason, before the initialization phase, we assume that the green bond ecosystem participants have agreed to an access policy published in the blockchain and enforced during the transactions. Furthermore, each stakeholder maintains a node of the system and acts either as a validator or an issuer. Additionally, regulators participate in the process as external observers.

The key-players of the system are the following, Capgemini (2016):

- **Issuers:** Creates and administers green assets and shares quantitative impact reports using clear metrics and units. He can also integrate external audits and reviews.

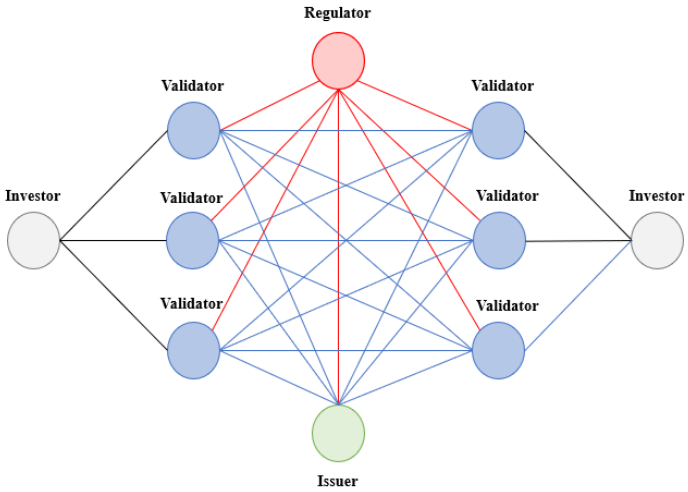


Fig. 2: Blockchain participants inter-connectivity

- **Validators:** Are responsible to validate impact reports on project and framework level and also the delivery on green commitments and green debt strategies.
- **Investors:** Creates investment portfolios, can make investment discoveries, manages assets and monitors asset impacts.
- **Regulators:** Oversees the consensus formation ensuring compliance and regulatory control. The regulator has a veto ability and is authorized by the participants to stop a block formation when misbehaviour ascertains.

The above mentioned general roles could include other more specific. For example, issuers of a green bond could be a bank, a company or a syndicate; validators could be rating agencies, regulators could be legal counsel etc. The inter-connectivity of the participants is shown in Fig. 2.

The system combines the roles of the Mandated Lead Arranger (MLA) or the passive bookrunner. It is responsible for Origination, issuance of securities, book building and allocation processes taking place in the classical model.

The participants' contradicted nature leads to numerous functional and security requirements, especially from the aspects of efficiency and inviolability of the procedure. Validators, on the one hand, need assurance that all the procedures were made according to the predefined policy, while investors, on the other hand, need assurance that their investment has an added value towards green development. Moreover, the ecosystem must be supported by a mechanism that guarantees that no foul play is made (e.g, a malicious investor buying coupons with no real money), providing an audit trail for each transaction made and safeguards in case of verified misbehavior.

3.2 The bond issuance process in the blockchain structure

This section will describe the two basic processes taking place in the classical bond issuance model, syndication and auction in short. To clarify the proposed architecture's processing flow, we will also describe the matching of these procedures with the proposed blockchain-enabled model.

3.2.1 Syndication process

A book-runner organizes the syndicate in syndication use-case, possibly inviting other banks to combine into a managing group.

This process is commonly used by companies and other organisations as a way to trade debt for fund raising. The main characteristic of Syndication approach, is that a bank consortium, that acts as intermediary, is responsible to drum up demand from investors and at the end, when the bond reaches maturity, the banks must buy what is left. The issuer has the benefit that the full amount requested will be raised regardless the demand, while the banks gain a significant amount of fees.

The fee splits into management fees, underwriting fees, and selling concessions. It is calculated from the extracted differences on the prices the bonds are sold to consortium banks. For example, a bond issue with an issue price € 5,000 (at par) and gross spread 3%, is purchased by the book-runner at € 4,850 (when €150 gross of spread is calculated). Then the bond is sold to underwriters at € 4,860 (with €10 as management fee) and at sellers for €4,890. Finally, sellers can sell the bond to investors at €4,900 gaining €10 as selling concession.

The process is as follows, first a book-runner receives the mandate by a prospective issuer. Then they discuss with each other the terms of the issuance, for example what will be the type of the bond, adjusting the maturity, the number of coupons etc. Finally, the book-runner organizes the managing group (syndicate) and in case the bond is not rated by an independent authority, makes preparation for shaping credit opinion about the issue.

The announcement of the issuance terms starts the book-building process. However, details about the bond characteristics are still to be defined in the origination phase and are released just before the book-building starts. At the end of the book-building period, final terms are decided, and the bond is priced.

The pricing of a bond is usually expressed in terms of credit spread, which is the difference between the interest rate paid and the risk-free rate with the same maturity. On the offering day, the syndicate purchases the issuer's bonds, though the issuer will not receive the funds until the closing day.

3.2.2 Auction process

The auction process is usually followed by governments wishing to issue and sell bonds. The date of the auction is announced well in advance — many countries publish annual auction schedules.

Prices for the debt are set by the auction process, reflecting the prevailing market at the time. Prospective buyers of the bond — large banks are known as primary dealers acting on behalf of investors — submit pricing bids and, after the auction has closed, the government's debt management organisation then divides the bond between the bidders, taking the highest prices first and working downwards until it has raised its target amount.

Auctions and syndicated deals are linked in part through banks. By acting as a primary dealer in bond auctions, banks can build relationships with sovereigns to win mandates for syndicated issuance, which come with attractive fees. The demand level in the market is the key factor for countries to decide which process to choose. In less liquid markets or less common types of bonds — such as longer-dated issuance, larger amounts of issuance, index-linked bonds, or issuance by emerging market countries — putting together a syndicate is, therefore a more certain way of ensuring that the issuer can raise the finance successfully.

3.2.3 Syndication and Auction in the blockchain

The goal of the proposed blockchain-enabled framework is to eliminate intermediaries without compromising the services offered' sustainability and credibility. The two procedures described in the Sections 3.2.1 and 3.2.2 must therefore be simulated with autonomus way.

The syndication process is supported by correlating multiple issuers in the same bond issuance. As a first step, issuers get to decide the terms of the bond. Each bond's term sheet is published on the blockchain with a digital form through a smart contract function and remains pending until the validators perform the checking and publish the impact reports. Regulators oversee the compliance to the predefined policies. The process starts with the publication of the green bond and it's term sheet in the blockchain. The bond gets archived in the blockchain when maturity, conversion or issuer liquidation function are enabled.

The auction process is more similar to decentralized crowdfunding systems. As in the previous use-case, the first step of the procedure is to publish the blockchain's bond. According to the demand, an initial price is set to the bond's coupons and the price up-scales or down-scales. Note that banks and also the government's debt management organisation act as validator nodes.

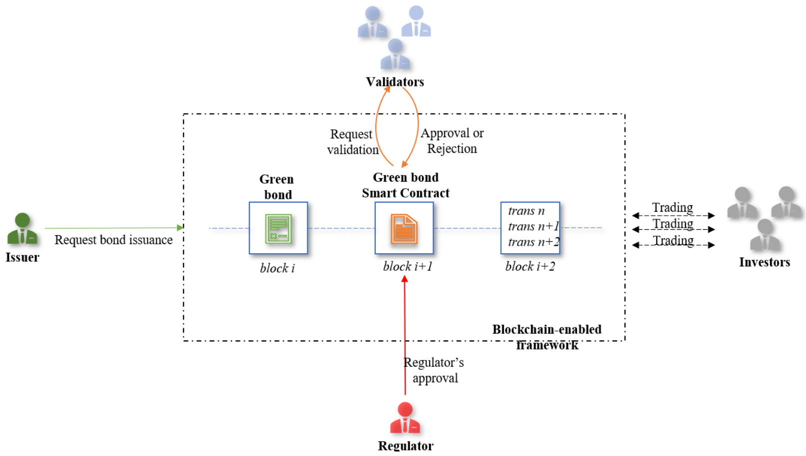


Fig. 3: High level architecture

3.3 Architecture description

The architecture is based in a five step model from green bond initialization to archiving.

The stages of the blockchain-enabled model are:

- **Initialization:** Is the first step, were the bond issuer (or syndicate) decides a bond issuance with the corresponding terms and makes the appropriate demand.
- **Preparatory:** Validators assess the investment's impact in green economy and issue a report. Financial checks are performed by the validators.
- **Launching:** Once the issuer has fulfilled all the requisite documentation, regulator's approval is sought. Regulator checks the digital bond and enforces compliance with the predefined policy if needed. The digital bond is published and is open for trading.
- **Trading:** Transactions over the bond's coupons are executed and remain pending for system settlement. Validators process the transactions and store the transaction information on the blockchain. Additionally, fund transfers for coupon payments and redemption can be made on this stage.
- **Archiving:** All the transaction history is archived on maturity, conversion or redemption. Audit trails remain on the blockchain for regulatory compliance.

As shown in Fig. 3 the issuer interact with the Green Bond Smart Contract (GBSC) in order to set the system in motion. Then validators and the regulator provide approval based on the documents presented, before the bond is published. Finally after the issuance the investors can start trading.

Table 1: Green Bond Smart Contract main functions

Function	Actor	Input	Output	Description
constructor	All	-	-	Sets the structure and the limitations with *require* clauses
registration	All	personal certificates	UID	Links the user with a unique system ID
bondIssuance	All	documentation	Bond	Handles the process of validation and issuing
changeLoopLimit	Owner	Loop limit	Loop limit	Through this function the owner can define or alter the loop limit
mintBond	Owner	Buyer address, Bonds amount	Minted Bonds	The owner can define how many bonds to mint
redeemCoupons	All	Array of Bonds	Redeemed coupons	This function defines the redeem coupons on bonds
transfer	All	Receiver's address, Array of Bonds	Transferred	This function transfers bonds to the buyer
getLastTimeRedeemed	All	Bond id	Last time redeemed	This function returns when was the last time coupons of a particular bond were redeemed
getBondOwner	All	Bond id	Bond owner	This function returns who is the owner of a specific bond
getRemainingCoupons	All	Bond id	Remaining coupons	This function returns how many coupons remain to be redeemed for a specific bond
getCouponsRedeemed	All	Bond id	Redeemed coupons	This function returns how many coupons were redeemed for a specific bond
getTokenAddress	All	-	Token address	This function returns the address of the token that is redeemed for coupons
getMaturity	All	Bond id	Maturity date	This function returns the maturity date for a specific bond
getSimpleInterest	All	-	Simple interest	This function returns how much money is redeemed on a coupon
getCouponRate	All	-	Coupon rate	This function returns the yield of a bond
getTotalDebt	All	-	Total debt	This function returns the current unpaid debt

4 Experiments and Implementation

The correlation among the participants of the green bond ecosystem was implemented with the use of Smart Contracts, and tested in a local private blockchain.

Specifically, to implement the services offered by the proposed system, we have developed an Ethereum-based simulation environment using *node*[6] and *ganache-cli*[7], we also used *truffle*[8] to develop a fully functional smart contract. Additionally, we used ERC-20 from OpenZeppelin [9] for the tokenization.

4.1 Smart Contract implementation

For the needs of the use-case scenario examined, we have developed the *Green Bond Smart Contract* (GBSC), which processes the pre-issuance and post-issuance services, with a periodic distribution of interest payments to bondholders and the repayment of par value when the bond's maturity date is reached. In a separate smart contract, we implemented the forensic services. The main functions are presented in Table 1.

The registration service, linked with the *registration* function of the SC, assures that all users must first present legal identification through eligible certificates before they can initialize the process of bond issuance or trading.

For the bond issuance service, the *bondIssuance* function, handles the prerequisites of validators and regulator approval based on the documentation presented and the parameters of rate, maturity requested by the issuer. Through the *changeLoopLimit* and *redeemCoupons* functions the issuer can adjust the bond's loop and redeemed coupons accordingly.

Through the GBSC, investors can be informed about the maturity level, the rate and the par of a specific bond. Moreover, they can gain insight into the bond's impact report to the green economy. However, we should note that the scheme developed has severe limitations, especially from the aspect of security, which could be the subject of future work. The code developed is available on GitHub.

4.2 Tokenization

To adjust the processes of bond issuance to a blockchain-enabled model, we need to tokenize the bonds. When the legal documents get verified by the system's validators, the bond is ready for tokenization. The digital token is created through a smart contract with a specific standard (in our case ERC-20). Then the bond tokenization procedure takes place, and the participants

[6] https://nodejs.org/
[7] https://github.com/trufflesuite/ganache-cli
[8] http://truffleframework.com
[9] https://docs.openzeppelin.com/contracts/3.x/api/token/erc20

can start the trading phase. In a previous step, investors should exchange their money with tokens through a digital wallet. The last step of the procedure is the reverse tokenization (redemption), where the tokens are traded back for real money.

4.3 Tailored forensics

The system should provide audit trail services and transaction integrity for all actions (successful or not) taking place in the system. The blockchain has, by-design, an embedded mechanism for storing transactions logs on-chain. This default mechanism, however, has limitations for the specific use-case scenario of bond issuance. For example, the timeline of a bond lifecycle is difficult to be exported since transaction logs don't follow a specific pattern. Logs are registered in the system with a predefined structure that includes only the traders' ethereum addresses. To overcome these limitations, along with the GBSC we have developed a separate SC that manages and stores the transaction logs. This SC acts as an extra layer on top of the predefined blockchain structure, enabling each bond to bind to a chain of custody. This approach simplifies bond trailing for external auditors.

5 Discussion

In this section, we provide a brief qualitative performance analysis (across different metrics like efficiency, security, auditability etc.) of our architecture. We also discuss the various challenges to overcome in the blockchain bonds issuance area for broader adoption. Last but not least, we mention various limitations of our approach and fruitful areas for future research.

5.1 Performance analysis

The proposed blockchain-enabled architecture offers significant advantages and has an untapped potential to improve trust and efficiency in bond issuance processes by simplifying ownership recording and coupon payment processing. In particular, the various smart contracts within our blockchain-enabled architecture minimize the overall handling of bonds issuance processes and provide increased automation and faster transaction execution. Consequently, issuance-related costs are minimized, and smart contracts' self-executing capabilities safeguard trust among all the stakeholders involved. The proposed architecture also presents significant benefits in terms of interoperability by fostering the integration of heterogeneous bond issuance records across the entire bond issuance ecosystem. Another important aspect of our architecture is its distributed trust management functionalities. Finally, it incorporates a forensics mechanism tailored to all the stakeholders involved' accountability needs. This mechanism can keep all bond issuance activities and with strong integrity guarantees, thus improving regulatory compliance while eliminating the parties' opportunistic behavior.

Blockchain can also ensure green bond issuance transparency, thus serving as an instrument for fueling the sustainability transition. Apart from transparency, the proposed architecture also offers significant improvements in terms of auditability (auditable transaction records that can be inspected by regulators). The overall system also considers various regulatory compliance instruments and enhances access of regulatory bodies to issuance records.

5.2 Challenges for broader adoption of blockchain-enabled green bond issuance frameworks

Although blockchain is expected to play a pivot role in the financial industry, many issues remain unaddressed, particularly impediments for broader adoption of blockchain-enabled green bond issuance frameworks. Regulatory uncertainty seems, at least for the moment, the greatest impediment to blockchain adoption in financial markets. It should be noted that blockchain's innovative nature creates numerous problems for financial regulators. Broader adoption of blockchain technology would necessitate changes to regulatory frameworks to fully comply with the various legal requirements Seretakis (2019). Regarding the blockchain-enabled bonds issuance process, there is a current lack of regulatory clarity on digital assets and tokens HSBC and Sustainable Digital Finance Alliance (2019). Regulatory frameworks designed to protect investors, like, for instance, the custody issue identified during the World Bank/CBA issuance, may prevent participation in bonds over blockchain HSBC and Sustainable Digital Finance Alliance (2019). Lack of standardization is also an important barrier to blockchain adoption in bonds market. Standardization is crucial in the case of green bonds where common standards for reporting should be used not only for evaluating the "greenness" of a project but also for assessing the tangible environmental benefits once a green investment has made. Blockchain standardization is closely related to compatibility with legacy systems and the challenge of replacing existing legacy systems or establishing interoperability with existing infrastructures, given the various operational and cost constraints, should not be underestimated Seretakis (2019).

Another significant barrier to blockchain adoption is the scalability issues prevalent to large-scale blockchain implementations (especially to public blockchain networks). Blockchain scalability-related issues include block size, response time, the volume of transactions (throughput) and high fees. Such issues pose significant challenges to blockchain developers and blockchain early adopters as the network grows every day, and the number of users increases in various real-life blockchain applications. For improving the scalability of blockchain applications, some researchers have proposed the usage of private blockchain networks Dong et al. (2019). Scalability is a key-challenge in current blockchain-enabled bond markets where available blockchain applications can't meet the requirements of today's market infrastructures and maintain the current volume of transactions HSBC and Sustainable Digital Finance Alliance (2019). Note that current bond issuance blockchain applications are isolated and largely “home-grown” within banks, thus limiting investors’ reach. For a wider adoption of blockchain technology, future blockchain-enabled platforms should also be interoperable, apart from scalable and new channels are needed to reach new types of investors HSBC and Sustainable Digital Finance Alliance (2019).

Other barriers stem from the intrinsic characteristics of blockchain technology. For example, settlement of trade of bonds on a blockchain would be much faster than conventional practices that necessitate 2-3 days on average. Unfortunately, this improvement in speed offers an adversary or a thief the ability to resell a stolen security almost in real-time. Note that with conventional certificated securities, a thief would take several days to resell the stolen securities Ryan and Donohue (2017). Settlement finality seems also incompatible with blockchain technology. Settlement finality ensures that a transaction made over a network will, at some point, be complete and not subject to reversal. Blockchain networks rely on probabilistic consensus mechanisms where participants are allowed to contribute to the ledger’s updating, and it can take from 10 minutes to 4-6 hours for participants to confirm transactions. Therefore, a clear and transparent moment of finality does not exist in blockchain networksSeretakis (2019). The immutability of blockchain is also a challenge, particularly in light of privacy-related regulatory frameworks like the EU’s General Data Protection Regulation (GDPR). For instance, personal data storage on a blockchain network contradicts GDPR and the so-called ”right to be forgotten” Politou et al. (2018). Apart from GDPR, the increased transparency and auditability of blockchain networks render any personal data (relevant to transaction activities or assets) completely linkable to a certain person HSBC and Sustainable Digital Finance Alliance (2019).

5.3 Limitations

The proposed architecture presents some limitations worth mentioning. For example, from a security standpoint, we haven’t applied strong authentications and authorization mechanisms in our architecture. For the future, we intend to incorporate in our system fine-grained access control policies for all the stakeholders involved to strike a better balance between security and operability (for example, using attribute-based encryption approaches). The proof-of-concept implementation we have provided is limited to only the blockchain part of our system, and other functional components were left aside. In the near future, we plan to implement a large scale implementation with extended use cases from the bonds market to validate our architecture’s scalability further. Finally, it should be noted that although we made use of tokens for totally managing the ownership of the bonds, we have partially used blockchain for payments and settlement (i.e., we kept some bond issuance activities of-chain).

6 Conclusions

In this paper, we have proposed an efficient blockchain-enabled architecture for managing green bonds issuance. We have digitized the overall bonds issuance process by using a set of fully functional smart contracts. Apart from the standard services for bond issuance, our architecture also provides various traceability and auditability functionalities and a strong forensics-by-design mechanism, features not supported by conventional bond issuance schemes. For developing our architecture, we have taken into account various real-life operational requirements and the inherent complexities prevalent to the bonds issuance ecosystem. For demonstrating the applicability of the proposed architecture, we have designed a proof-of-concept implementation. The experimental results have demonstrated the potential of the proposed architecture to handle the depth and breadth of bond issuance operations in an efficient and trusted manner.

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