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A blockchain framework for increased trust in green bonds issuance

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ABSTRACT
Bond issuance is a highly technical and complicated process, including disparate regulatory frameworks, limited traceability and auditability, settlement failures, and mutually untrusted stakeholders. Green bond issuance presents additional challenges, as the qualification of a bond as ”green,” third-party verification is needed to guarantee that the proceeds fund environmentally beneficial projects. This implies additional administrative and compliance costs. Blockchain technology can address some of the issues mentioned above, to establish trust in impact reporting green bond processes. To this end, we propose a blockchain-enabled green bond issuance architecture that safeguards investors' confidence in the bond's green credentials while keeping the issuer from being accused of greenwashing. To adjust the process of bond issuance to a blockchain-enabled model, we 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 offer forensic-by-design services. The overall system also considers various regulatory compliance instruments and enhances the access of regulatory bodies to issuance records.

KEYWORDS
Fintech, green finance, tokenization

1. Introduction

Green bonds are an essential financial tool for funding environmental projects through a low-carbon financing approach (Reboredo 2018). Similar to any other bond, green bonds are financial securities in which the bond issuer sells a contract promising repayment and a specified rate of interest (Sanderson 2018). In particular, 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 positive environmental and/or climate benefits range from building wind and solar farms to developing sea walls in cities threatened by rising sea levels. Green bonds provide

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investors with the benefit of knowing that the proceeds of their investment are being used in an environmentally positive way and with significant financial gains. Although green bonds currently represent only 2% of total bond issuance worldwide, they have still been considered a critical financial instrument since they facilitate sustainable investing for a multitude of institutional investors (Foster 2019).

During the last decade, green or climate bonds have gained significant momentum. In 2014, Unilever issued a £250M green bond to halve the amount of waste, water consumption, and greenhouse gas emissions generated by existing factories. In 2017, Apple issued a $1bn green bond to finance renewable energy and energy efficiency improvements throughout its facilities and supply chain. According to the Climate Bonds Initiative, the long-awaited $1 trillion in annual green investment will occur in 2023. There is no question why Morgan Stanley referred to this type of bond as the "green bond boom" (Morgan Stanley 2017).

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. Green bonds follow the Green Bond Principles stated by the International Capital Market Association (ICMA), and the proceeds from the issuance of a green bond 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 recent studies, green bond 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, financial gain is more prominent for corporate issuers, and it persists in the secondary market (Gianfrate and Peri 2019). To scale up the green bond market, however, an increase in investors' green awareness and governmental tax-based incentives will be necessary (Agliardi and Agliardi 2019).

1.1. *Motivation and contribution*

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-known initiatives include the Corda ecosystem (a distributed ledger platform designed to record, manage, and synchronize financial agreements between regulated financial institutions) and various blockchain-enabled security issuance initiatives. It is expected that the fintech-related blockchain market size will grow from $231.63 million in 2017 to $6,700.63 million by 2023, at a compound annual growth rate of 75.2% during the forecast period (Market Research Future 2020). In partnership with the Commonwealth Bank of Australia, the World Bank issued the first bond created, allocated, transferred, and managed throughout its life-cycle using blockchain technology[1]. In early 2019, Santander issued the first blockchain-enabled green bond Santander (2019).

Bond issuance is a highly technical and complicated process, entailing mutually untrusted stakeholders with sometimes conflicting objectives (Van der Wansem et al. 2019).

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

Currently, the global bond market is faced with several pain points when it comes to bond 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 bond issuance processes ((International Organization of Securities Commissions 2019)). Financial assets are usually replicated multiple times in disparate systems maintained by different entities, possibly in different jurisdictions. This historically induced proliferation and diversification of records and account relationships of financial assets provides ample opportunity for inefficiencies and operational and legal risk (Paech 2017). Limited traceability and auditability also present significant pain points in the overall bond issuance process. Due to the increased number of intermediaries (issuing agent, paying agent, and "Bill & Deliver" agent), which centrally keep records of financial instruments, it is complicated to trace a person's entitlement to a financial instrument. Bond issuance costs (regulatory, certification, transactions, reporting, verification, systemic, settlement, and back-office fees) limit bond returns. Settlement failures, disputes, conflicts of interest (allocation conflicts), and reconciliation errors are just a few of the various operational and counterparty risks associated with bond issuance (International Organization of Securities Commissions 2019). Besides, many potential issuers have limited knowledge of the green bond issuance process (Climate Bonds Initiative and International Institute for Sustainable Development 2016). Finally, current bond issuance practices rely on inefficient, manual, multiple-step processes that, apart from being time-consuming, are also prone to errors (Shaikh and Zaka 2019).

Green bond issuance has much in common with conventional bond issuance. However, green bond issuance presents additional challenges when compared to traditional bond issuance processes. In particular, for a bond to be qualified as a "green" bond, third-party verification is needed to guarantee that the proceeds fund environmentally beneficial projects, which implies additional administrative and compliance costs. Lack of common standards may increase confusion, and green bond issuers are faced with reputational risk if the green integrity of the bond or the bond's green credentials are questioned (Kaminker et al. 2017). Another key challenge facing green bond 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). World Bank leads an initiative to standardize green bond impact reporting, although the standardization of the reporting procedure cannot compensate for weaknesses in the underlying data. Other initiatives include the European green bond standard, published by the European Commission, and the Green Bond Principles, published by ICMA. In Table 1, we present the overall challenges and issues related to the bond issuance process (including green bonds).

Blockchain technology can address some of the issues mentioned above, especially as an instrument for establishing trust in impact reporting green bond processes. To this end, we propose a blockchain-enabled green bond issuance architecture that safeguards investors' confidence in the bond's green credentials while keeping the issuer from being accused of greenwashing. 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. In particular, the proposed architecture:

Pain points of current (green) bond issuance schemes	Explanation
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). - 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).
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
Limited process automation	Manual multiple-step processes where all changes made to issuance process should be updated across all the layers of custody. 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.
Trust	Limited traceability of the performance of green assets. Lack of investors' confidence in the bond's green credentials and possible issuer accusations of greenwashing

Table 1.: Current pain points in (green) bonds issuance process

- Acts as a transparent yet fully controllable decentralized authority where the funds of qualified, environmentally friendly projects can be traced. In particular, the proposed architecture considers the various aspects and the complexity of the bond issuance procedures and the particular requirements of green bonds (traceability and transparency in the allocation of proceeds).
- Is versatile enough to accommodate multiple use case scenarios (could be used, apart from green bonds, in any bond issuance process). The blockchain-enabled architecture offers increased automation and security in bond issuance while reducing intermediary costs. It also offers improved transaction speed and reduced transaction costs.
- Provides strong integrity guarantees and forensics-by-design capabilities. The system provides audit trail services and transaction integrity for all issuance processes taking place, acting as a single source of truth.
- Serves as a risk mitigation instrument for the overall bond issuance process, especially for preventing opportunistic behavior in bond pricing (resulting in under or overpricing) and minimizing counterparty and operational risk (clearing and settlement failures, disputes, reconciliation errors, long settlement cycles, increased number of intermediaries, etc.).

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 bond 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 broader adoption of blockchain technology in the financial sector, with a focus on bond issuance. The paper ends with some concluding remarks.

2. Literature review

Blockchain technology, a foundational technology of the Fourth Industrial Revolution, is expected to play a crucial role in various domains (Casino et al. 2019). 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 to green bond issuance can be split into 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 trusted third parties currently manage in a relatively 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 compared to non-blockchain bond issuance approaches. The most significant 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 more accessible collection and sharing of data for supervisory purposes (Seretakis 2019). Capgemini (2016) notes that by incorporating unique security identifiers into trade lifecycle processes, blockchain technology could also facilitate the implementation of a unique reference system in securities markets by incorporating unique security identifiers into the unique security identifiers.Particular focus has also been paid to corporate bond issuance. Market participants explore the issuance and trading of corporate bonds using blockchain technology, particularly for automating the calculation and payment of coupons and redemption (Workie and Jain 2017). Blockchain technology usage 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 the issuance and sale of securities on a blockchain.

From a sustainability point of view as well, blockchain technology is considered a game-changer in securities issuance (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 can help scale climate action and traceability-by-design features to enhance the impact validation of green bond issuance, thus, unlocking more significant funding opportunities in green projects (Climate Bonds Initiative and International Institute for Sustainable Development 2016). Blockchain technology is expected to simplify green bond issuance processes by improving the overall issuance processes' traceability 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 multiple stakeholders (Zhang et al. 2018). Other exciting blockchain-related initiatives include the so-called "forest bonds," representing financial instruments aimed at stopping deforestation (Sanderson 2018).

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, drives 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 aims to develop a versatile and efficient system that significantly reduces the intermediary costs and offers compliance, scalability, confidentiality, and security. Besides, the system acts as a transparent (among the participants) yet fully controllable decentralized authority. Our proposed architecture considers the various aspects and the complexity of the bond issuance procedures and the special requirements of green bonds (by inserting reports that predict the impact on the green economy with predefined metrics). In particular, the proposed system combines the roles of the Mandated Lead Arranger (MLA) and the passive bookrunner. It is responsible for the origination, issuance of securities, book building, and allocation processes of the classical model.

This section presents our architecture structure and the key players who participate in the system and the processes. It is worth noting that we have considered compliance with UCC section 8-401(a), which distinguishes us from other blockchain applications in terms of anonymity in our scheme.According to UCC, the issuer of blockchain security must know the owner's identity. Furthermore, the transferor's identity of the blockchain securities cannot be anonymous in order for 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)).Therefore, a private blockchain structure was selected, allowing transparency between the participants while maintaining anonymity outside of the ecosystem.

3.1. *Requirements and key players*

The bond exchange ecosystem involves various participants who often have different or even contradictory goals; thus, the system must enforce trust. For this reason, before the initialization phase, we assume that the green bond ecosystem participants have agreed to an access policy published on the blockchain, which is then enforced during the transactions by an access control function stored in a smart contract. This function acts as an access control list that authorises data access (regarding the bond and the issuers' details) depending on the role. Furthermore, each stakeholder maintains a node in the system and acts either as an external validator or an issuer. Additionally, regulators participate in the process as external observers. The key players in the system are the following (Capgemini 2016):

- **Issuer:** Creates and administers green assets and shares quantitative impact prediction reports using clear metrics and units along with the proper documentation for the bond in question. The issuer can also integrate external audits and reviews.
- **External Validator:** Is responsible for validating impact prediction reports at project and framework level and also delivering a report for green commitments and green debt strategies based on the documents provided by the issuer. If the prediction impact report passes the validation procedure, the signed report gets published on the blockchain; otherwise, the report is rejected.
- **Auditor:** Independent third party (ITP) that can provide official and consolidated Know-Your-Customer (KYC) checks.
- **Investor:** Creates investment portfolios, can make investment discoveries, manages assets and monitors asset impacts.
- **Regulator:** Oversees the formation of consensus while also ensuring compliance and regulatory control. Regulator also has a veto right and is authorized by the participants to stop a block formation when misbehaviour is ascertained.

The general roles mentioned above could include other more specific ones. For example, an issuer of a green bond could be a bank, a company, or a syndicate. An external validator could be a rating agency, and a regulator could be legal counsel. Note that the validators, described as the system's key players, are entirely different from the validators that form the consensus committee of the blockchain for validating the blocks. Consensus is achieved among the nodes of the system through an automated procedure that validates the block formation. The interconnectivity of the participants is shown in Fig. 1.

Considering the system's requirements and the contradicted nature of the partici-

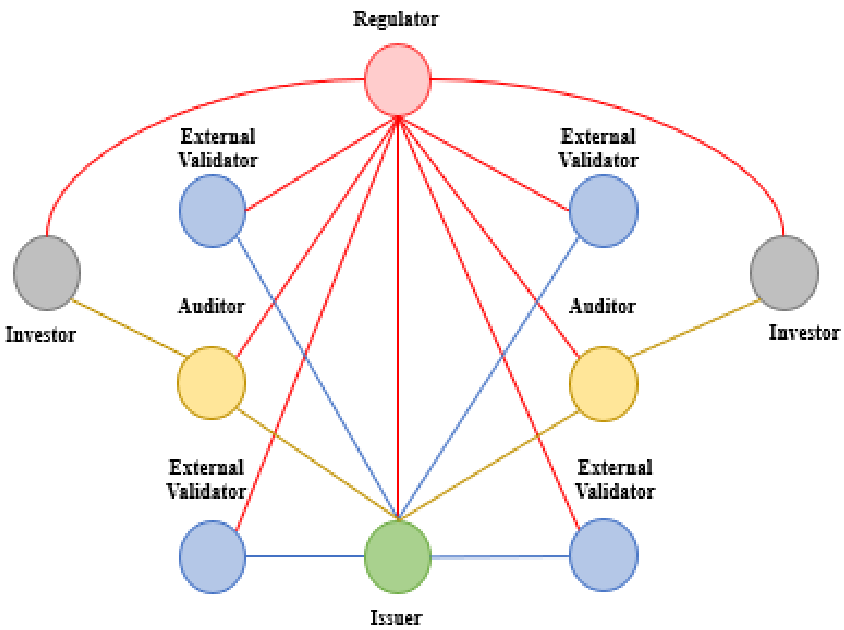

Figure 1.: Blockchain participants' inter-connectivity

pants, we can distinguish numerous functional and security goals, especially from the aspect of efficiency and inviolability of the procedures. The functional requirements demand that the system be efficient enough to handle multiple transactions and support real-time processes. Furthermore, it should be able to store and process mid-range data (e.g., documents) or link them to an external source, guaranteeing data integrity (e.g., storing a hash of the document on-chain). From the participants' perspective, external regulators, on the one hand, need assurance that all the procedures put into the system are compliant with the regulations and follow a predefined policy agreed upon by the stakeholders in advance. On the other hand, investors require proof that their investment has added value towards green development. Moreover, the ecosystem must be supported by a mechanism that prevents foul play (e.g., a malicious investor is buying coupons with no real money), provides an audit trail for each transaction made, and safeguards cases of verified misbehavior.

3.2. *The bond issuance process in the blockchain structure*

In this section, we describe in short the two fundamental processes in the classical bond issuance model: syndication and auction. To clarify the proposed architecture's processing flow, we also describe the matching of these procedures with the proposed blockchain-enabled model, along with a high-level description of the process flow.

3.2.1. Syndication process

A bookrunner organizes the syndicate in a syndication use-case, possibly inviting other banks to combine into a managing group. Companies and other organizations commonly use this process as a way to trade debt for fundraising. The syndication approach's main characteristic is that a bank consortium that acts as an intermediary is responsible for drumming up demand from investors. In the end, the banks must buy what is left. The issuer has the benefit that the total amount requested will be raised regardless of the demand, while the banks gain a significant fee.

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

The process is as follows: first, a bookrunner receives the mandate from a prospective issuer. Then they discuss the terms of the issuance, for example, the type of the bond, adjusting the maturity, the number of coupons, etc. Finally, the bookrunner organizes the managing group (syndicate) and, in case the bond is not rated by an independent authority, prepares to shape 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 released just before the book-building starts. At the end of the book-building period, final terms are decided, and the bond is priced. Bond pricing is commonly expressed in terms of credit spread, which is the difference between the interest rate paid and the risk-free rate for bonds of the same maturity.The syndicate purchases the issuer's bonds on the offering day, 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. After the auction has closed, the government's debt management organization 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 critical factor for countries to decide which process to choose. In less liquid markets, less common types of bonds, or emerging market countries, putting together a syndicate is a more certain way of ensuring that the issuer can successfully raise the capital.

3.2.3. Syndication and Auction in the blockchain

The proposed blockchain-enabled framework aims to eliminate intermediaries without compromising the sustainability and credibility of the services offered. As a result, the two procedures described in Sections 3.2.1 and 3.2.2 must therefore be simulated autonomously. At the beginning of the process, all participants must first register with the system and obtain credentials. Each time a new green bond issuance request is made, the auditors initiate a KYC procedure to verify the issuers' credibility.

The syndication process is aided by multiple issuers in the same bond issuance.As a first step, issuers get to decide the bond terms and the corresponding impact prediction report. Each bond's term sheet is published on the blockchain digitally through a smart contract function. It remains pending until the external validators perform the checking, signing, and publication of the impact prediction report. Regulators oversee compliance with the predefined policies and regulations. They can also intervene when there are inconsistencies and exercise the right of veto. The process starts with the publication of the green bond on the blockchain. Bonds' term sheet and the signed impact prediction report are published on the decentralized storage infrastructure. For integrity needs, a hash of the accompanying documents is stored on the blockchain. Investors can start trading, and the bond gets archived on the blockchain when maturity, conversion, or issuer liquidation functions are enabled.

The auction process is more similar to that of decentralized crowdfunding systems. As in the previous use case, the first step of the procedure is to materialize and publish the green bond on the blockchain along with the terms sheet and the signed impact prediction report. According to the demand, an initial price is set for the bond's coupons, and the price either goes up-scales or down-scales. Note that banks and also the government's debt management organization act, in this case, as external validators nodes.

3.3. *High level description of the proposed architecture*

As a first step, the main actors (issuers and investors) must register with the system by providing their certificates to the *registration* function of the *Green Bond Smart Contract* (GBSC). The system provides a unique identifier (UID) for each user.

Then the main processes of the proposed architecture are based on a five-step model, from green bond initialization to archiving. The stages of the blockchain-enabled architecture are the following:

- **Initialization:** Is the first phase, where the bond issuer (or syndicate) decides on a bond issuance with the corresponding terms and makes the appropriate demand. At this stage, the issuer is responsible for providing an impact prediction report for the specific green bond he wants to issue.
- **Preparatory:** In this phase, two procedures take place. Firstly, external validators assess the investor's predicted impact on the green economy and publish a signed report on the decentralized storage infrastructure. Then auditors perform checks for the credibility of the issuer.
- **Launching:** Once the issuer has fulfilled all the prerequisite documentation, the regulator's approval is sought. The regulator checks the digital bond and enforces compliance with the predefined policy if needed. The digital bond has been published and is open for trading.
- **Trading:** Transactions over the bond's coupons are executed and remain pending for system settlement. All transaction-related information is stored on the blockchain. Additionally, fund transfers for coupon payments and redemption can be made at 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. 2, the issuer and the investor interact with the GBSC to register in the system. For this purpose, they use their digital wallet address and provide valid certificates. Then the registered issuer interacts with the GBSC to set the system in motion. Specifically, the issuer defines the terms of the green bond and provides the proper documentation. External validators and regulators then provide approval based on the documents presented and the regulatory compliance before the bond is published.

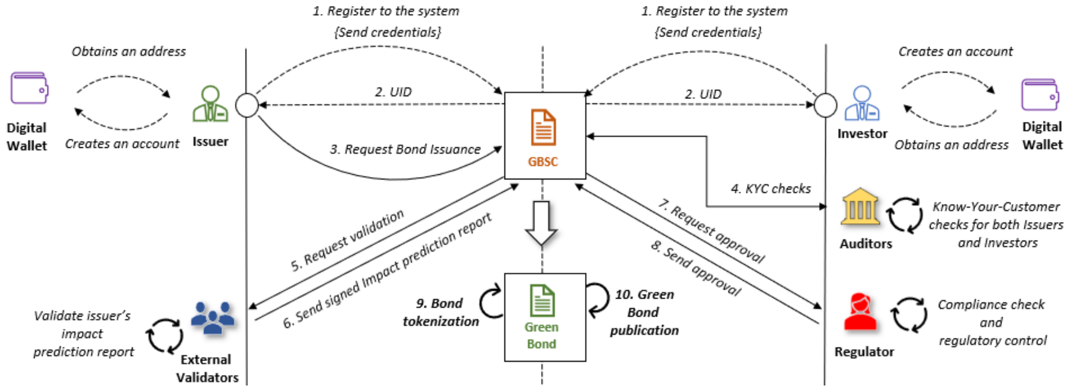

Figure 2.: High level architecture for Green Bond issuance procedure

Finally, the green bond gets published on the blockchain, and the investors can start trading. All transactions are stored on the blockchain.

4. Experiments and Implementation

The various interactions among the participants of the green bond ecosystem were implemented using smart contracts, and tested in a local private blockchain developed in Ethereum platform, with Proof of Work as the underlying consensus mechanism. Specifically, to implement the services offered by the proposed architecture, we have developed an Ethereum-based simulation environment using *node*[2] and *ganache-cli*[3] and also used *truffle*[4] to develop three fully functional smart contracts. For developing our proof-of-concept, we used ERC-20 from OpenZeppelin [5], mainly for taking advantage of the homogeneity provided from this specific token type. However, we should note that a different tokenization approach could be used. For example, using ERC-721 tokens would add unique features in the digital bonds published on the blockchain, but this was beyond the scope of our research.

Note that the consensus algorithm in a blockchain network defines how the participants reach an agreement regarding the state of the ledger. Various consensus algorithms exist that present advantages and disadvantages. Proof of Work, for example, used in the Bitcoin network, offers strong security but a low transaction rate. We have chosen to use the Ethereum network for our proof of concept implementation (which runs on Proof of Work as well). However, we should note that our platform is affected by the consensus mechanism only in terms of performance. Therefore, choosing other approaches (e.g. Hyperledger with Proof of Elapsed Time or the forthcoming Ethereum 2.0 with Proof of Stake) could strengthen the platform's performance metrics, especially in a large scale implementation.

4.1. *Green Bond Smart Contract*

For the needs of the use-case scenario examined, we have developed the GBSC, which processes the pre-issuance and post-issuance services, with a periodic distribution of

[2]https://nodejs.org/
[3]https://github.com/trufflesuite/ganache-cli
[4]http://truffleframework.com
[5]https://docs.openzeppelin.com/contracts/3.x/api/token/erc20

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 2. In this sub-section, we analyze the basic functions and services included in GBSC.

The *constructor* function can be called and executed only once (when the smart contract is deployed). This is the first set of code that is executed for the contract in question and is used to initialize the contract state and set the global parameters.

The registration service, linked with the GBSC's *registration* function, ensures that all users must first present legal identification through eligible certificates before initializing the process of bond issuance or trading.

For the bond issuance service, the *bondIssuance* function handles the prerequisites of external validators and regulators' approval based on the documentation presented and the parameters of rate and maturity requested by the issuer. Through the *changeLoopLimit* and *redeemCoupons* functions, the issuer can adjust the bond's loop and redeem 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 on the green economy. The code developed is available on GitHub[6].

4.2. *Impact prediction reports and document storage*

To overcome blockchain storage limitations, the necessary documentation for the bond issuance is stored in *IPFS* [7]. This mechanism is resistant to tampering and censorship by design, allowing our system to maintain its decentralized nature. In this decentralized storage infrastructure, each bond's impact prediction reports and accompanying documentation are stored. A unique fingerprint called a content identifier (CID) and a hash of the data are stored on the blockchain, guaranteeing integrity. The CID is used to link the data with the specific green bond issued.

Impact prediction reports are the main element differentiating the implementation procedure for green bonds compared to regular bonds. These reports detail how the bond's specific investment will aid in the transition to a more sustainable environment, generating impact and addressing climate change challenges. Impact reports, in general, include both qualitative performance indicators and quantitative performance measures and are updated regularly to inform investors about the progress of the investment. According to the green bond standard issued by the (European Commission 2020), impact reports must include information regarding the issuer and the bond (e.g. project name, description, sector and environmental objective, total cost, etc.) and also, if available, impact metrics.

As a pre-issuance requirement in our system, we implemented impact prediction reports to inform investors about the anticipated impact of each bond. Green bond issuers are responsible for submitting these reports to initiate a new bond issuance procedure. Reports are stored on IPFS and sent to an external validator for verification. Then, as previously discussed, the external validator can sign or reject the given report. When a green bond is published in the system, potential investors can access the corresponding signed impact prediction report. A final report is issued at the archiving phase.

[6] `https://github.com/bagmalamas/Green-Bond-Issuance`

[7] `https://ipfs.io/`

4.3. *Tokenization and bond digitization*

To adjust the processes of bond issuance to a blockchain-enabled model, we need to tokenize the bonds. Tokenization is the process of digitally representing the bond using a digital token on our blockchain platform (Davydov and Yanovich 2020). When the legal documents are verified by the system's external 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 can start the trading phase. In the previous step, investors should exchange their money for tokens through a digital wallet. The last step of the procedure is reverse tokenization (redemption), where the tokens are traded back for real money.

4.4. *Tailored forensics*

The system should provide an audit trail for services and transaction integrity for all actions (successful or not) taking place in the system, acting as a single source of truth. This requirement is crucial for ensuring that no user can deny the ownership and validity of their actions. Tailored forensics is a service that verifies the origin and integrity of transactions. Blockchain has, by design, an embedded mechanism for storing transaction logs on-chain. This default mechanism, however, has limitations for the specific use-case scenario of bond issuance. For example, a bond life-cycle timeline is challenging to export since transaction logs do not follow a particular 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 smart contract, *Tailored Forensics Smart Contract* (TFSC), that manages and stores all transaction logs with a predefined structure. TFSC acts as an extra layer on top of the blockchain structure, enabling each bond to be bound to a chain of custody. This approach also simplifies bond trailing for external auditors.

5. Discussion

Investors ask for ever-tighter impact reporting, which implies closer and closer definitions of green bond use of proceeds and firmer segregation of assets funded by green bonds from general corporate balance sheets. Additionally, the asset-backed loans have to be closely monitored as any proceeds from selling the bond will be used for an environmentally friendly purpose. Therefore, the traceability and transparency offered by blockchain technology throughout the green bond issuance process are critical because they boost investors' confidence in the bond's green credentials while keeping the issuer from being accused of greenwashing.

Apart from transparency and traceability, the proposed blockchain-enabled architecture offers significant advantages and has the 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 bond 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 serves as a single source of truth, especially by boosting investors' confidence in the bond's green credentials while safeguarding transparent reporting on the allocation of proceeds. 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. The architecture incorporates a forensics mechanism tailored to all the stakeholders involved' accountability needs. This mechanism can keep all bond issuance activities and solid integrity guarantees, thus improving regulatory compliance while eliminating the parties' opportunistic behavior. The proposed architecture also offers significant improvements in auditability (auditable transaction records that regulators can inspect).

5.1. *Challenges for broader adoption of blockchain-enabled bond issuance frameworks*

Although blockchain is expected to play a pivotal role in the financial industry, many issues remain unaddressed, particularly the challenges of successfully implementing blockchain-enabled applications (Biswas and Gupta 2019). In the sequence, we present an analysis of the various challenges prevalent in current blockchain implementations in the financial sector, focusing on bonds and green bond issuance. It's important to note, though, that the problems below only apply to current blockchain platforms. We expect that future blockchains will be free of these problems, especially from a technical point of view.

Regulatory: Regulatory uncertainty seems to be the most significant barrier to blockchain adoption in financial markets, at least for the moment. 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, especially for tokenized securities (Seretakis 2019). Regarding the blockchain-enabled bond 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). In general, there is a need for regulatory frameworks that make it possible for digital securities to be registered and treated as financial securities.

Governance: Blockchain governance seems to be the biggest single challenge for the growth of distributed ledgers (Zachariadis et al. 2019). Blockchain governance refers to the way disparate stakeholders within the same blockchain project achieve coordination, direction, and control (Pelt et al. 2021). Not only does blockchain governance necessitate consensus among validating nodes, but it also necessitates consensus among network users. It should be noted that blockchain governance differs fundamentally different from traditional contractual and relational governance (Lumineau et al. 2021). Practically, the debate over governance in the context of blockchain networks currently revolves around two pillars: centralized vs. decentralized and on-chain vs. off-chain. For example, public blockchain platforms like Ethereum are governed on a distributed basis in line with their autonomous and decentralized operations, leading to issues due to the lack of a central legal entity with formal responsibility for the system. During times of crisis, the risks of such a governance scheme can be amplified as the system's developers try to agree on software code changes to address the problem (Zachariadis et al. 2019). Off-chain governance mechanisms include public discussion and collectively agreed-upon updates, whereas on-chain governance mechanisms entail online voting (stakeholders vote using tokens to either accept or reject a proposed change).

The various incentives (miner rewards, transaction fee-setting mechanisms, etc.) provided to the participating entities are of particular interest to financial blockchain networks. In general, blockchain incentives can be either monetary or non-monetary (privileges, visibility, reputation, etc.) (Beck et al. 2018). Apart from issuers and investors with a clear incentive to participate in bond issuance, other market players require additional motivation. Auditors would be compensated with a flat fee for each KYC check they conduct. Regulators may collect a predetermined monetary sum for overseeing each bond trading procedure during the finalization phase. Innately, this is contingent on the bond's successful issuance. External validators will be compensated in advance by the issuer and may earn credibility tokens based on the outcome of the finalization procedure. Acquiring credibility tokens may improve their chances of being selected for the next round of impact prediction report validation.

Standardization: Lack of standardization is also an essential barrier to blockchain adoption in the bond market. Standardization is crucial in the case of green bonds, where common standards for reporting should be used to evaluate the "greenness" of a project and assess the tangible environmental benefits once a green investment has been made. Given the various operational and cost constraints, the challenge of establishing interoperability with existing legacy systems or infrastructures should not be underestimated (Seretakis 2019).

Scalability: Another significant barrier to blockchain adoption is the scalability issues prevalent in large-scale blockchain implementations (especially public blockchain networks). Blockchain scalability-related issues include block size, response time, the volume of transactions (throughput), and high fees. Such problems pose significant challenges to blockchain developers and early adopters as the network grows every day and the number of users increases in various real-life blockchain applications. Some researchers have proposed the use of private blockchain networks to improve the scalability of blockchain applications (Dong et al. 2019). Scalability is a critical challenge in current blockchain-enabled bond markets where available blockchain applications cannot meet today's market infrastructures' requirements and maintain the current volume of transactions. Note that existing bond issuance blockchain applications are isolated and primarily grown within banks, thus limiting investors' reach (HSBC and Sustainable Digital Finance Alliance 2019). In the near future, blockchain platforms based on faster consensus mechanisms will eventually address scalability challenges, high gas fees, and transaction congestion (like, for instance, the forthcoming Ethereum 2.0 platform to be released in 2022).

Energy consumption: Concerns have been raised during the last few years about the amount of energy consumed by blockchain networks. Energy consumption represents a significant cost item for participating stakeholders, especially in vast financial networks. Arguably, the amount of energy consumed by a blockchain network is determined by the underlying consensus mechanism. For example, the Ethereum blockchain network, which uses the Proof of Work (PoW) consensus mechanism, will undergo a complete overhaul this year, reducing energy consumption by nearly 99%. The new Ethereum 2.0 blockchain network will be based on a Proof of Stake (PoS) system, which will be faster and more environmentally friendly.

Settlement finality: 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 thief the ability to resell 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 also seems 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 can contribute to the ledger's updating, and it can take anywhere 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 networks (Seretakis 2019).

Immutability: 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 stored on a blockchain network contradicts GDPR and the so-called "right to be forgotten" (Politou et al. 2018). Aside from GDPR, the increased transparency and auditability of blockchain networks make any personal data (relevant to transaction activities or assets) completely linkable to a specific person (HSBC and Sustainable Digital Finance Alliance 2019). Another critical aspect of blockchain immutability may refer to the possible software errors or bugs embedded within smart contracts, which are impossible to change (see, for instance, the Ethereum decentralized autonomous organization 50M USD theft that occurred in 2016). Since loopholes and bugs can never be avoided entirely, systemic stability necessitates the prevention of "incorrect" results in a blockchain financial network or, at the very least, the ability to reverse such results (Paech 2017).

5.2. *Limitations*

The proposed architecture presents some limitations worth mentioning. We have not applied strong access control mechanisms (authentications and authorization) in our architecture from a security standpoint. Although build-in functions in our smart contracts offer significant access control features (like the *get* function), we believe that fine-grained access control is the optimal solution. Fine-grained access control policies are paramount, especially for multi-entity, multi-role ecosystems where information sharing occurs among disparate and untrusted parties/stakeholders. 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. Shortly, we plan to implement a large-scale implementation with extended use cases from the bonds market to validate our architecture's scalability further along with sound governance schemes. Although we used 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). Finally, a challenging extension of our blockchain-enabled architecture could address the secondary bond market, in which one of the main risks is the settlement failure, that many economists addressed in the past (e.g., Fleming and Garbade (2002), Fleming and Garbade (2005), Trimbath (2011)).

6. Conclusions

In this paper, we have proposed a blockchain-enabled architecture for managing green bond issuance. Our approach can be used for any bond, but since green bonds have a clear mandate to use the capital raised for green investments, it is essential to introduce an issuance process that guarantees it. We have digitized the overall bond issuance process by using tokens and 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 robust forensics-by-design mechanism, features not supported by conventional bond issuance schemes. Therefore, investors in green bonds can be confident that the funds raised will be used for environmentally-friendly projects and that the issuer will report on the impact on the environment. We have considered various real-life operational requirements for developing our architecture and the inherent complexities prevalent in the bond issuance ecosystem. By designing a proof-of-concept implementation, we demonstrate the applicability of the proposed architecture. Experimental results have shown the proposed architecture's potential to efficiently handle the depth and breadth of green bond issuance operations in a trusted manner.

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Function	Actuator	Input	Output	Description
constructor	-	-	-	Is executed only once when the Smart Contract is deployed. Initializes contract state and sets global parameters
registration	Issuers, Investors External validators Regulators Auditors	Valid personal certificates	UID	Links the user with a unique system ID
bondIssuance	Issuers	Impact prediction report, bond documentation	Green Bond	Handles the processes of external validations and issuance of the green bond
changeLoopLimit	Issuers (Green Bond Owner)	New Loop limit	Updated Loop limit	Defines or alters the loop limit of a bond
mintBond	Issuers (Green Bond Owner)	Buyer's address Bonds amount	Minted Bonds	An issuer can define how many bonds to mint
redeemCoupons	Issuers (Green Bond Owner)	Array of Bonds	Redeemed coupons	Sets the amount of redeem coupons
transfer	Issuers (sellers) Investors (buyers)	Buyer's address Array of Bonds	Update ownership details	Transfers ownership from seller to buyer when certain prerequisites are fulfilled (e.g. the price is payed)
getLastTimeRedeemed	Issuers, Investors External validators Regulators Auditors	Green Bond's address	Last time redeemed	Returns details regarding the last time coupons of a particular bond were redeemed
getBondOwner	Issuers, Investors External validators Regulators Auditors	Green Bond's address	Green Bond's owner address	Returns the address of the owner for a specific bond
getRemainingCoupons	Issuers, Investors External validators Regulators Auditors	Green Bond's address	Amount of pending coupons	Returns the amount of coupons that are not yet redeemed
getCouponsRedeemed	Issuers, Investors External validators Regulators Auditors	Green Bond's address	Amount of redeemed coupons	Returns the amount of redeemed coupons
getTokenAddress	Issuers, Investors External validators Regulators Auditors	Token's id	Token address	Returns the address of the token that is redeemed for coupons
getMaturity	Issuers, Investors External validators Regulators Auditors	Green Bond's address	Bond's maturity date	Bond's maturity date Returns the maturity date for a specific bond
getSimpleInterest	Issuers, Investors External validators Regulators Auditors	Green Bond's address	Simple interest	Returns how much money is redeemed on a coupon
getCouponRate	Issuers, Investors External validators Regulators Auditors	Green Bond's address	Coupon rate	Returns the yield of a bond
getTotalDebt	Issuers, Investors External validators Regulators Auditors	Green Bond's address	Total debt	Returns the current unpaid debt

Table 2.: Green Bond Smart Contract main functions.