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11 Designing a framework for a blockchain-based voluntary carbon credit lifecycle

Abstract: Voluntary Carbon Credits (VCCs) are essential tools in combating climate change, enabling carbon offsetting and incentivising sustainable investments. However, their traditional lifecycle is hindered by challenges such as limited verifiability, transparency, and trust, which compromise effectiveness and market integrity. This research introduces a blockchain-based framework that leverages immutability, transparency, and efficiency. Using the Design Science Research (DSR) methodology, we developed a holistic framework incorporating smart contracts, decentralised file systems, and oracles to optimise key lifecycle processes. We defined ten Design Objectives (DOs) for the pre-issuance phase, post-issuance phase, and the entire VCC lifecycle, addressing challenges and requirements like privacy and regulatory compliance. The evaluation confirmed that all DOs were met, demonstrating significant potential for improving transparency, efficiency, and accountability. However, further research is needed to explore the most suitable blockchain type, advanced technologies like Zero-Knowledge Proofs for privacy or rollups for scalability, as well as business model considerations such as cost and pricing structures to ensure financial stability and practical viability.

Keywords: Voluntary Carbon Market (VCM), Voluntary Carbon Credit (VCC) lifecycle, blockchain, tokenisation, prototype

1 Introduction

Voluntary Carbon Credits (VCCs) have emerged as a crucial instrument in global sustainability efforts, offering a market-based mechanism for mitigating greenhouse gas emissions.[1] Given the urgent and existential threat posed by climate change, VCCs fa-

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cilitate the offsetting of carbon footprints by enabling entities to invest in projects aimed at carbon reduction or sequestration.[2] The increased stringency of emission reduction targets under international frameworks such as the Paris Agreement has further amplified the importance of VCCs.[3] These credits serve not only as a tool for environmental accountability but also as a driver of investment in sustainable practices and technologies, thereby integrating economic incentives with ecological preservation.

Despite their potential, VCCs face significant challenges related to verifiability, transparency, and trust.[4] The verifiability of VCCs is compromised by the complexities involved in accurately measuring and validating the emissions reductions achieved by offset projects.[5] The VCC markets are often lacking transparency due to different standards and platforms, leading to questions about the legitimacy and efficacy of certain credits. Consequently, trust in VCCs is undermined by instances of fraud and the circulation of credits that fail to deliver genuine environmental benefits.[6] An investigation into Verra, the leading certifier for forest carbon offsets, revealed that over 90% of their rainforest offset credits are 'phantom credits', meaning they do not result in actual carbon reductions and may exacerbate global warming.[7] The study, conducted by The Guardian, Die Zeit, and SourceMaterial, found significant discrepancies between Verra's claims and the actual impact on deforestation, raising serious concerns about the validity of offsets used by major corporations like Disney, Shell, and Gucci. These issues undermine the credibility of the VCC system and hinder its effectiveness as a tool for carbon mitigation.

Against this backdrop, blockchain technology presents promising affordances for addressing some of these fundamental problems of VCCs. By providing an immutable and transparent ledger, blockchain can enhance the traceability of carbon credits, ensuring that each credit corresponds to measurable emission reductions.[8] Tokenisation of VCCs, being the digital representation of an asset on a blockchain, could facilitate more efficient trading and reduce administrative overhead, thus improving market efficiency.[9] These integrations are essential to realise the full potential of blockchain in creating a robust and reliable VCC system.

Despite the potential blockchain might offer with tokenisation, existing VCC tokens have yet to achieve substantial market adoption. Due to failed initiatives and negative publicity of projects such as the Toucan Protocol, which involved tokenised retired credits, the market has recently seen a decline.[10] This observation is corroborated by academic literature, highlighting the fragmented and often deficient design of current VCC token solutions. For example, studies on initiatives like KlimaDAO reveal significant shortcomings, including inadequate lifecycle management, poor interoperability, and a lack of regulatory compliance.[11] These deficiencies underscore the necessity for more comprehensive and integrative design approaches to VCC tokenisation. As blockchain technology is not a panacea, it often requires integration with complementary technologies such as decentralised file systems for secure and scalable file storage[12] or trusted oracles that provide accurate and reliable off-chain data.[13]

Consequently, the objective of our research is to propose a holistic VCC token concept that addresses the entire lifecycle of carbon credits, leveraging blockchain technology and integrating additional technologies as needed. Our aim is to resolve the prevalent issues of verifiability, transparency, and trust, thereby enhancing the efficacy and reliability of the VCC market. By designing a comprehensive system that integrates these elements, we aim to create a more reliable and effective market for VCCs, thereby enhancing their role in global sustainability efforts. Concretely, this book chapter strives to answer the following research question:

RQ: How to design a blockchain-based VCC token system to comprehensively address the lifecycle of carbon credits and enhance verifiability, transparency, and trust in the VCC market?

Our approach is grounded in the Design Science Research (DSR) methodology.[14] We begin by collecting requirements for a successful VCC token design from relevant literature and industry standards. Utilising these requirements, we design our artefact and evaluate it against predefined design objectives (DOs) to ensure its practical relevance and effectiveness. The structure of the remaining chapter is as follows: After a brief dive into the background of VCC markets and the tokenisation, we review existing literature to identify key challenges and requirements; subsequently, we present our proposed design; this is followed by an evaluation of its performance; and finally, we discuss the implications of our findings and propose directions for future research.

2 Background

2.1 Understanding VCC market

VCCs have emerged as an important tool in global efforts to reduce carbon emissions, offering a market-based approach for organisations and individuals to offset their carbon footprint. As certificates representing the reduction of one ton of CO_2, they can be voluntarily purchased by individuals or organisations to offset their emissions.[15] This process involves a comprehensive lifecycle with six phases: project design, registration, monitoring-reporting-verification (MRV), issuance, transaction, and retirement.[16] During the initial *design* phase, developers planning environmental projects conduct a comprehensive feasibility assessment to evaluate the potential impact of their proposed carbon reduction efforts.[17] Based on the outcomes of this assessment, developers select an accredited standard provider, such as Verra or the Gold Standard, and submit the project during the *registration* phase to ensure compliance with the methodologies and criteria established by the respective standard-setter.[18] Once registered, the project enters the *MRV* phase, where project developers measure and report key

metrics on the development of the project and third-party auditors verify the accuracy of emissions reductions and confirm that the project is meeting its environmental commitments.[19] Upon successful completion of the MRV phase, carbon credits are issued to the project developers within the *issuance* phase.[20] These validated carbon credits can then be traded in carbon markets during the *transaction* phase.[21] Developers may choose to sell the credits directly in over-the-counter (OTC) transactions or via intermediaries, such as brokers, who may either sell them directly to end buyers or aggregate them into portfolios for broader market distribution.[22] Ultimately, end buyers, such as corporations or individuals aiming to offset their carbon emissions, can enter the *retirement* phase of the carbon credits by permanently removing them from circulation, thereby fulfilling their carbon offset obligations.[23]

As illustrated by the lifecycle, standard-setting programs play a pivotal role in maintaining the reliability and integrity of carbon credits by rigorously verifying their achievement of intended environmental and sustainability objectives. However, the market's supply side remains highly fragmented due to the presence of multiple, often divergent standards. Prominent organisations such as Verra and the Gold Standard are key players in this space. Although both organisations aim to ensure the quality, transparency, and positive impact of carbon credits, they differ in their specific areas of focus, programs, and methodologies.[24] Verra emphasises advancing sustainable development and climate action, while the Gold Standard is particularly renowned for its stringent integration of environmental impacts with the social and economic benefits of carbon offset projects.[25] Beyond Verra and the Gold Standard, a variety of other registries operate, including the American Carbon Registry (ACR), Climate Action Reserve (CAR), Carbon Trust, Plan Vivo Standard, and the Climate, Community & Biodiversity (CCB) Standard.[26] These organisations also provide certification and validation of carbon credits, ensuring their quality and transparency. Each registry offers a unique focus, whether it be on community development, biodiversity conservation, or specific regional initiatives, contributing to the diversity of the carbon offset certification landscape.

This fragmented market landscape has significantly increased the demand for enhanced transparency, liquidity, and integrity. In response, several initiatives have emerged to introduce standardisation across various stages of the carbon credit lifecycle, aiming to address these challenges effectively. A notable example is the EU Carbon Removal Certification Framework, adopted in 2024.[27] This framework seeks to establish rigorous certification and verification standards for carbon removal projects across European markets and to implement a uniform registry that enhances transparency in emission reductions while preventing double-counting, which occurs when the same credit is claimed more than once within or across markets.[28] The London Stock Exchange's Voluntary Carbon Market Designation is another key initiative aimed at creating a standardised framework for reporting processes that entities must adhere to qualify for market participation. This designation ensures that only entities meeting strict reporting standards can participate, thereby enhancing the

market's reliability and transparency. Additionally, there is a global push to standardise trading mechanisms, as presented by initiatives such as Japan's GX League and Australia's Carbon Exchange.[29] These efforts include the creation of centralised trading platforms that facilitate the buying and selling of carbon credits, making transactions more efficient and transparent. There are also initiatives, such as the Voluntary Carbon Markets Initiative, which, among other efforts, focus on developing guidelines for claiming carbon offsets, especially during the retirement phase.[30] This standardisation is crucial for preventing greenwashing and ensuring that companies provide clear, accurate information about their carbon reduction efforts. However, many of these initiatives are concentrated on specific regions or stages of the carbon credit lifecycle, leaving significant gaps in the broader market. The World Bank's Carbon Assets Tracking System (CATS) seeks to address this issue by offering an ambitious international solution designed to integrate both voluntary and compliance carbon markets.[31] The main goal of CATS is to create a transparent and reliable platform for the issuance, recording, and tracking of emissions reductions across all standard programs throughout the entire VCC lifecycle on a global scale. At this moment in time, however, CATS is in development and limited to World Bank climate finance programs, such as the Forest Carbon Partnership Facility, restricting its applicability in the broader international VCC market. Finally, while the ongoing standardisation efforts work to unify the market, an alternative technological solution gaining momentum is the blockchain-based tokenisation of carbon credits, which also seeks to continuously improve the transparency, traceability, liquidity, and integrity of the market.

2.2 Blockchain and tokenisation of VCCs

Blockchain technology is a decentralised and fault-tolerant distributed ledger technology, which has significantly reshaped various industries by utilising public key cryptography and consensus protocols to ensure secure and transparent transactions.[32] Its append-only structure, linking blocks with hash pointers, creates an immutable ledger that fosters trust and eliminates the need for a central authority.[33] This technology underpins systems like Bitcoin and Ethereum, enabling secure cryptocurrency transactions and facilitating applications such as tokenisation. Tokenisation, which represents real-world assets as digital tokens, enables fractional ownership, enhances transaction efficiency through smart contracts, and promises to democratise access to assets. The integration of blockchain and tokenisation is thereby revolutionising traditional finance and ownership paradigms, promoting decentralisation, transparency, and efficiency.[34]

The underlying asset of a token can encompass blockchain-native assets in the form of cryptocurrencies as well as off-chain assets, which exist outside of the blockchain, such as traditional financial assets like stocks, bonds, or real estate.[35] As outlined in the previous section, one off-chain asset that has seen both investigation and

practical implementation as a token is the VCC. Tokenising VCCs has the potential to address several key challenges by leveraging blockchain technology, whose core characteristics directly align with these challenges. In a tokenised system, VCCs are represented as digital tokens on a blockchain.[36] Consequently, this system can use smart contracts to automate and streamline processes, such as validating carbon offset projects and ensuring compliance with regulations, thus reducing the risk of fraud and improving market confidence. Furthermore, blockchain provides a transparent and tamper-proof ledger, which can mitigate issues related to the verification and tracking of carbon credits.[37] By ensuring that every transaction is recorded immutably, blockchain technology can enhance trust among participants and reduce the administrative burden associated with carbon credit trading.[38] Additionally, tokenisation can increase market accessibility and liquidity, enabling more participants to engage in the VCC market and facilitating 24/7 trading without the need for intermediaries.

The market has already recognised all the mentioned benefits of tokenising carbon credits, leading to the development of various tokens.[39] Among them is Toucan's CO2 token (TCO2), which is based on the Verra methodology and operates on both the Polygon and Celo blockchains. Similarly, Gold Standard CO2 token (GCO2) is developed by Flowcarbon and offers an alternative tied to the standards set by Gold Standard. Moss CO2 token (MCO2) is another notable token, issued under the methodology for Reducing Emissions from Deforestation and Forest Degradation. However, this diversity of tokens highlights that the issue of market fragmentation remains unresolved, as it introduces additional complexity. Moreover, the implementation of blockchain technology presents its own set of challenges that must be carefully addressed. The integration of blockchain technology into the VCC market requires significant technical expertise and infrastructure investment, which can be a barrier for smaller organisations. Furthermore, the regulatory environment for blockchain and digital assets is still evolving, and uncertainties in legal frameworks can pose risks to the adoption of tokenised VCCs. Additionally, the environmental impact of blockchain, particularly proof-of-work systems, raises concerns about the sustainability of using such technology for environmental purposes.

In conclusion, while blockchain and tokenisation offer significant opportunities to enhance the VCC market by addressing challenges related to transparency, efficiency, and security, a comprehensive approach is needed to tackle the technical, regulatory, and environmental issues, as well as to mitigate the additional fragmentation they may introduce.

3 Method

In the development of a holistic VCC token concept, we adhered to the DSR methodology, as illustrated in Figure 11.1.[40] The goal of DSR is to address identified real-world prob-

lems through a build-and-evaluate process, leading to the creation of purposeful design artefacts and the generation of actionable and generalisable knowledge.[41] These artefacts can take various forms, such as constructs, models, methods, and instantiations, with prototypes being typical instantiations.[42] The DSR methodology is known for its systematic approach, which encompasses the iterative processes of building, evaluating, and refining artefacts.[43] This makes it an effective framework for tackling the complex challenges associated with VCC tokenisation. Our approach was informed by specific aspects of the DSR methodology, which helped ensure a structured and rigorous development process. DSR typically involves identifying a problem, designing a solution, and evaluating its effectiveness.[44] By adhering to these principles, we integrated insights from both practical examples and blockchain literature to inform our prototype development. This iterative process allowed us to derive generalisable knowledge through a structured evaluation, addressing the deficiencies of existing VCC mechanisms and tokenisation efforts.

The motivation for our research stemmed from the lack of comprehensive design concepts for VCC tokens and their practical applicability. Traditional carbon credit mechanisms and initial blockchain-based solutions, such as tokenised credits, currently suffer from issues related to verifiability, transparency, and trust.[45] These challenges underscore the need for a solution that leverages blockchain's capabilities while addressing its limitations. Our research was guided by the goal of developing a more effective blockchain-based solution to enhance the VCC market. To address these identified challenges, we derived DOs based on literature pertaining to carbon credits, blockchain technology, and past tokenisation efforts. In our technical analysis of current blockchain-based VCC concepts, we developed and refined identified DOs further, which finally guided the creation and evaluation of our VCC token..[46] By iteratively refining the prototype, we adhered to the DSR principle of continuous improvement, ensuring that it effectively addressed verifiability, transparency, and trust issues in VCC tokenisation. This process established a solid foundation for both practical applications and future development.

We finally conducted a thorough, logical analysis to evaluate our prototype, ensuring that the DOs were fulfilled. This evaluation provided valuable insights into the effectiveness of our reference implementation and the application of blockchain technology for VCC tokens. The iterative process was crucial for refining the prototype, ensuring its practical relevance and generalisability. This approach allowed us to transition from an instance-specific solution to a broader, more abstract framework, aligning with the DSR goal of producing generalisable knowledge.

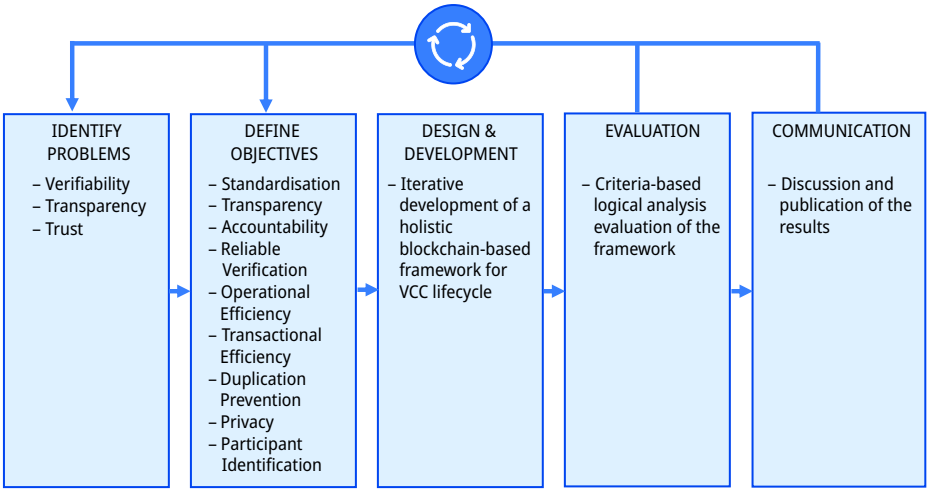

Figure 11.1: Our DSR Research Process.

4 Problem identification and design objectives

As previously outlined, the DSR process commences with the identification of relevant challenges that the designed prototype seeks to address. A comprehensive understanding of these challenges is crucial to establishing clear DOs that will systematically guide the development process, ensuring that the prototype effectively meets its intended purposes. To derive these DOs in a structured manner, this section follows the VCC lifecycle, with the findings summarized in Table 11.1. Initially, we conduct an analysis of the challenges associated with the entire VCC lifecycle to formulate overarching lifecycle DOs. Subsequently, we examine the pre–VCC-issuance phase (lifecycle steps 1–3), where the project design is developed and verified, followed by an exploration of the post-VCC-issuance phase (lifecycle steps 4–6), during which the VCC is issued, traded, and retired.

The first thing that stands out when analysing the existing standards in the VCC market is the fragmentation of the market itself. Although the overall VCC lifecycle follows a similar structure, different standards and methodologies are applied during the initial stages of the lifecycle, depending on the provider, such as Verra, Gold Standard, or the ACR. While Verra and ACR for example focus primarily on carbon reduction, with ACR concentrating exclusively on projects in the USA, the Gold Standard places a strong emphasis on delivering additional social and environmental co-benefits.[47] Based on the standards set by each institution, the MRV process, as well as the pool of verifiers, can vary. Additionally, the different registries and trading platforms further contribute to market fragmentation. As a result, trading occurs across multiple, often disconnected platforms or in OTC transactions, which makes it difficult

for buyers and sellers to connect and leads to inconsistent pricing, higher transaction costs, and reduced liquidity.[48] Consequently, a holistic VCC concept necessitates the consideration of diverse perspectives and the implementation of a *standardised process* that facilitates participation by all standard-setting organisations without barriers. Initiatives such as the London Stock Exchange Voluntary Carbon Market or the EU Carbon Removal Certificates proposal already aim to standardise processes, but they often fall short in terms of ensuring the transparency and integrity of the carbon credits themselves.[49]

The demand for transparency arises, especially within the initial pre–VCC-issuance phase. Although VCC programs have made several efforts to make project information and plans more publicly accessible, significant gaps remain, especially in the availability and accuracy of data.[50] For instance, while geospatial site boundaries are theoretically accessible through many offset programs, numerous projects fail to provide this information or supply corrupted or inaccurate data, undermining the credibility of the submitted project and the related VCCs. Moreover, the procedures for emission reduction measurements and the verification processes within the MRV have been subject to considerable criticism due to their opacity.[51] Therefore, the holistic VCC concept should incorporate full *transparency* in the initial pre–VCC-issuance phase, ensuring the information regarding project design, registration, and MRV process is clear and accessible.

However, transparency alone is not enough. It is imperative that the information provided during the initial phase is not only accessible but also immutable, thereby reinforcing the principle of transparency.[52] This means that once data is submitted, it should be securely stored in a way that prevents any alterations. The implementation of tamper-proof data systems is critical for safeguarding the integrity of the process, as it guarantees that all stakeholders are held accountable for the information they provide and the commitments they make.[53] Therefore, another key DO for the holistic VCC concept is establishing mechanisms that ensure rigorous *accountability* of all participants during the initial pre–VCC-issuance phase, ensuring the reliability of the provided data.

While ensuring that data is tamper-proof and transparent is essential, it does not inherently guarantee the integrity of the project design and the data themselves. In the conventional lifecycle of a VCC project, independent third parties play a critical role in validating and verifying the legitimacy of a project and its actual contribution to emission reduction.[54] These entities are also responsible for ensuring that the data presented in monitoring reports are accurate and that the project's commitments to emission reduction are faithfully adhered to throughout its operational period. However, significant concerns persist about the accuracy of data collection, the methodologies employed for measuring carbon emissions, and the overall verification process.[55] Critics have questioned whether the methods employed by verifiers are rigorous enough to ensure the credibility and accuracy of the projects, arguing that some may exaggerate or misrepresent their environmental impact by exploiting the complexity

and opacity of the verification process to appear more sustainable than they truly are.[56] Consequently, as another DO, it is essential to establish a *reliable verification process* that thoroughly assesses the legitimacy of the project, ensures the accuracy of the data in monitoring reports, and verifies that the project's commitments to emission reduction are genuinely met.

To build on the previously outlined DOs, it is crucial to supplement them with additional focus on operational efficiency. While transparency, accountability, and rigorous verification processes are fundamental to the integrity and success of the VCC lifecycle, these objectives must be reinforced by an efficiency requirement to ensure their practical implementation. Despite efforts by VCC programs to improve speed and efficiency, many processes remain hindered by outdated, manual methods like Excel spreadsheets and PDFs for data tracking.[57] These inefficiencies result in costly and time-consuming audits and verifications.[58] The reliance on such labour-intensive methods not only slows down the entire lifecycle but also increases the risk of human error, complicates data management, and creates unnecessary bottlenecks.[59] Hence, as an additional DO for the pre–VCC-issuance phase, incorporating *operational efficiency* is essential.

As the VCC lifecycle progresses into the post-issuance phase, the need for efficiency extends further, with a particular emphasis on optimising trading processes. After the issuance of VCCs, the traditional trading process frequently depends on financial intermediaries, such as brokers and carbon exchanges, which operate within formal hierarchies and can impose barriers that restrict accessibility to smaller projects and buyers in the carbon market.[60] Furthermore, the dependency on intermediary processes not only slows down the pace of trading but also drives up transaction costs, with commission fees ranging from 3% to 8%.[61] To enhance market liquidity by reducing entry barriers, transactional frictions, and costs, it is additionally necessary to introduce *transactional efficiency* as a further DO.

Furthermore, strengthening the connection to the earlier discussion on market fragmentation brings to light additional implications for the post-issuance phase that warrant further examination. The market's heterogeneity, coupled with the lack of established mechanisms that allow carbon credits to be recognised and utilised across various platforms and frameworks, makes effective interaction between these markets particularly challenging.[62] This lack of interoperability impedes the seamless exchange of carbon credits and diminishes market efficiency, which in turn complicates efforts to meet global climate goals. Therefore, it is vital to introduce *interoperability* as another core DO to facilitate global integration and ensure that carbon credits are consistently recognised and utilised across all platforms.

In addition to the challenges posed by the lack of carbon credit exchange among different platforms, the heterogeneity of markets significantly increases the risk of doubling carbon credits across various industrial and regional markets in the post-issuance VCC phase.[63] This issue arises when the same credit is counted and/or claimed more than once, either within a single market or across multiple markets, which can

undermine the integrity and effectiveness of global climate mitigation efforts. While the introduction of interoperability DO also partly addresses the issue of double-counting by requiring connected and harmonised markets, this objective is not specifically focused on the doubling issue. To ensure that the final prototype thoroughly addresses the risks associated with double-counting and double-claiming across different markets, it is essential to additionally introduce a DO specifically dedicated to *duplication prevention.*

At the same time, while the transparency requirement in the pre-issuance phase can be extended to the post-issuance phase to maintain the credibility of the VCCs, its scope of impact should be partially restricted. In this latter stage, openly sharing trading and transaction details across stakeholders may lead to concerns about confidentiality, competitive advantages, and market manipulation.[64] Balancing the need for transparency with the protection of sensitive information becomes crucial to maintaining trust and efficiency in the trading process while avoiding potential obstacles that could hinder market participation and effectiveness.[65] Consequently, a *privacy* DO is vital in the VCC transaction phase to safeguard sensitive information without compromising the overall transparency of the market.

Finally, it is essential to ensure that privacy measures do not obscure the identities of market participants, particularly when it comes to compliance and retirement purposes. The clear identification of all participants is crucial to prevent any entities from exploiting anonymity to misuse carbon credits, such as by fraudulently claiming multiple credits, engaging in money laundering, or financing illicit activities, which could undermine the market's integrity.[66] While it is important to maintain the confidentiality of negotiation details and trade specifics among the parties directly involved, this privacy must not extend to the point where it compromises regulatory oversight. Regulatory bodies responsible for compliance, such as anti-money laundering (AML) or counter-terrorist financing (CTF), must have full visibility into the identities of all participants to ensure that the market operates transparently and securely. This *participant identification* DO is the concluding one, providing a safeguard against any potential misuse of the system while balancing the need for privacy.

Table 11.1: Derivation of Design Objectives.

VCC – Lifecycle	Design Objectives	Description
Entire lifecycle	Standardised Process	A standardised framework is needed to harmonise the diverse standards and methodologies across the VCC market, ensuring consistency and accessibility without creating an entry barrier.[67]

Table 11.1 (continued)

VCC – Lifecycle	Design Objectives	Description
Pre–issuance phase	Transparency	Transparency in the initial pre–VCC-issuance phase is crucial for credibility. Persistent gaps in data availability and accuracy highlight the need for full transparency in project design, registration, and MRV processes to ensure clarity for stakeholders.[68]
	Accountability	The information provided during the initial pre–VCC-issuance phase must be immutable to ensure accountability. Tamper-proof data systems are essential to maintain data integrity and to hold all participants responsible.[69]
	Reliable verification process	Due to persistent concerns regarding data accuracy, carbon measurement methods, and the rigor of verification, a reliable process is essential to validate project legitimacy, ensure accurate monitoring, and verify adherence to emission reduction commitments.[70]
	Operational efficiency	Inefficient manual processes result in costly audits, human errors, and data management challenges, highlighting the need to enhance operational efficiency.[71]
Post–issuance Phase	Transactional efficiency	The reliance on financial intermediaries often restricts market access for small businesses, increases costs, and slows trading, thus highlighting the need for improved market liquidity, reduced frictions, and lower costs.[72]
	Interoperability	Interoperability is needed to address the lack of cross-platform recognition for carbon credits, facilitating seamless exchanges, improving market efficiency, and ensuring their consistent use across various platforms.[73]
	Duplication prevention	The heterogeneity of markets increases the risk of double-counting and double-claiming carbon credits across sectors and regions. Therefore, implementing duplication prevention is crucial to safeguard the integrity of global climate mitigation efforts.[74]
	Privacy	Sharing transaction details in the post-issuance phase can raise concerns over confidentiality and competitive advantage, underscoring the need for privacy measures to protect sensitive information while maintaining overall market transparency.[75]
	Participant identification	Regulatory visibility is crucial for AML and CTF compliance, necessitating clear participant identities to prevent misuse like fraud or money laundering while maintaining a balance with privacy.[76]

5 Design and development

Building on the identified DOs, we developed a holistic, conceptual blockchain-based framework for the VCC lifecycle. To enhance comprehension, the textual concept is supported by a visual illustration.[77] A logical view, shown in Figure 11.2 and discussed in the first subsection, clarifies stakeholders and components, while a procedural view, represented in Figures 11.3, 11.4, *and* 11.5 and covered in the second subsection, depicts the VCC lifecycle itself.

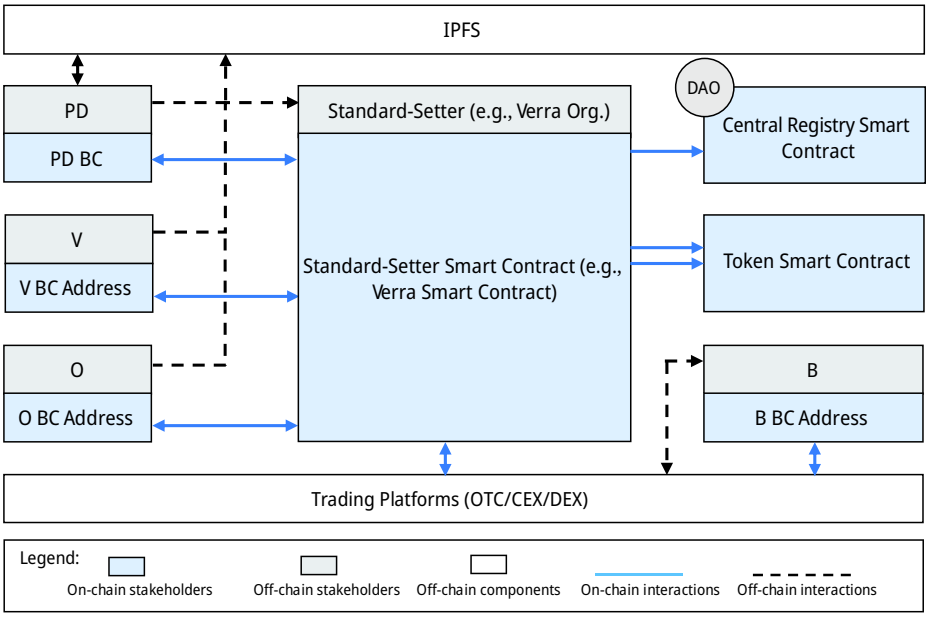

Figure 11.2: Logical View of Architectural Stakeholders and Components.

5.1 Prototype architecture: Stakeholders and components

Figure 11.2 illustrates all real-world actors in grey, while their corresponding blockchain addresses and general smart contracts are shown in light blue. The white-coloured boxes indicate actors and systems that operate outside the blockchain. Furthermore, the black dashed lines represent interactions that occur off-chain, while the thick blue lines represent interactions that occur on-chain with the corresponding stakeholders and components. The key stakeholders in this framework include *project developers (PD), verifiers (V),* the *standard-setters*, such as Verra Org., and the final *offset buyers (B).* To offer trading flexibility and diverse access options for buyers, our trade flow supports multiple forms of trading, including OTC trade, central exchanges

(CEX), and decentralised exchanges (DEX), all grouped under the *Trading Platforms (OTC/CEX/DEX)* category. This approach allows buyers and project developers to choose the right trading method based on their individual preferences.

In addition to the regular stakeholders, *oracles (O)* are integrated to provide off-chain data, such as satellite imagery, to ensure that the blockchain-based concept has access to real-world information. Oracles act thereby as bridges between the blockchain and external data sources, enabling the system to automatically verify and incorporate relevant off-chain information.[78] Furthermore, since standard-setters in a traditional VCC lifecycle handle large volumes of project-related documents and information, which would be too costly to store directly on the blockchain, we integrated the *InterPlanetary File System (IPFS)* to manage this data efficiently. IPFS is a distributed peer-to-peer file storage system that enables PDs and Vs to upload files, which can be distributed across nodes, ensuring data integrity and availability.[79] The file must first be uploaded to an IPFS node and pinned to ensure it remains accessible. During the upload process, IPFS splits the file into smaller chunks, hashes each chunk, and combines them into a single Content Identifier (CID). This CID acts as the address linking all related chunks. Because the CID is content based, any change to the file will result in a new CID, enabling easy verification of the file's integrity. To finally retrieve the file, users such us final buyers or other standard-setters can simply request it using the CID, and IPFS will locate and deliver the file from any node storing it, ensuring data integrity and providing a cost-efficient, decentralised storage solution.

By utilising the outlined off-chain components such as IPFS, key stakeholders can optimise the three types of on-chain smart contracts, namely: the Standard-Setter Smart Contract (SC), the Token SC, and the Central Registry Smart SC. *The Standard-Setter SC*, such as the Verra SC, incorporates core VCC lifecycle functions that should be consistent across all Standard-Setter SCs for the standardisation DO. These functions include project and report submission through CID provision, verifier assignment, verification, and registration of the credits. Simultaneously, it provides standard-setters with the necessary flexibility to customise the contract according to the specific methodologies and requirements, thereby reducing barriers to adaptation while maintaining standardisation requirement. For instance, standard-setters can decide whether they require more functions or whether verifier assignments occur automatically based on predetermined rules, or through a competitive application process, depending on their specific needs and preferences.

Another key standardisation feature integrated into the registration function of the Standard-Setter SC is the automatic initiation of the *Token SC* upon execution. The Token SC manages the project-specific token and includes standardised functions such as transfer and retirement, with the option to add custom features as needed. This approach ensures flexibility while maintaining a consistent framework for token management. To enhance traceability and duplication prevention, we opt for the use of standards that allow both fungible and non-fungible token (NFT) within the same contracts such as ERC-1155.[80] This standard enables the creation of unique tokens,

each with a distinct value, making it ideal for representing VCCs, where each project has its own unique characteristics and attributes. Additionally, the ability to support fungibility and fractionalisation is valuable for VCCs, as it allows credits to be divided into smaller units and traded more flexibly, increasing accessibility and liquidity for buyers and sellers. It is also further important to note that the Token SC must be set up in a way that allows initiation during the registration phase to allow trading of pre-issued VCCs. Since the subsequent MRV phase is lengthy and costly for PDs, they often seek funding early in the process.[81] By issuing the Token SC at this stage, PDs can trade VCCs to secure financing for their projects, effectively transforming them into issued VCCs after a successful MRV. Additionally, given that initial emission calculations are prone to risks like miscalculations or unforeseen environmental impacts, we also recommend incorporating buffer functions into the Token SC, following the model of the World Bank's CATS Program.[82] This feature helps protect against project underperformance, mitigates risks for buyers, and enhances the overall credibility of the VCC market.[83]

Finally, the standardised functions mentioned earlier are essential for *the Central Registry SC*, which acts as a central hub connecting the standard-setters' smart contracts. This connection is established through key functions of Standard-Setter SCs such as the submitting function, which automatically reports submitted projects to the central registry, or the registry function, which records the address of the initiated Token SC. By consolidating these functions' results in a single location, the Central Registry SC promotes transparency, simplifies traceability for all participants across various standards, and helps to prevent double-counting. To additionally ensure fairness, the Central Registry SC should be governed as a Decentralised Autonomous Organisation (DAO), where VCC owners hold governance rights and decide for example upon majority votes or a two-third majority, which standard-setters are to be included in this system. This governance model prevents standard-setters from monopolising or restricting entry to the central registry to limit competition. In contrast, VCC owners have an incentive to increase competition, as it fosters higher-quality standards.

5.2 Prototype functionalities: VCC lifecycle

Building on the previously discussed prototype components, the procedural view in Figures 11.3 *to* 11.5 provides a structured framework for analysing the system's functionality. The operational aspects of the design are divided into lifecycle phases and are examined using Verra as a practical example of a standard-setter, facilitating a step-by-step exploration of the VCC lifecycle. To further maintain visual consistency and easy reference, Figures 11.3 *to* 11.5 follow the same colour coding as Figure 11.2.

First and foremost, identifying all stakeholders through a KYC procedure is essential to ensure compliance with regulations such as AML and CFT, as formalised by the partitioner identification DO. This process is conducted off-chain, where key partici-

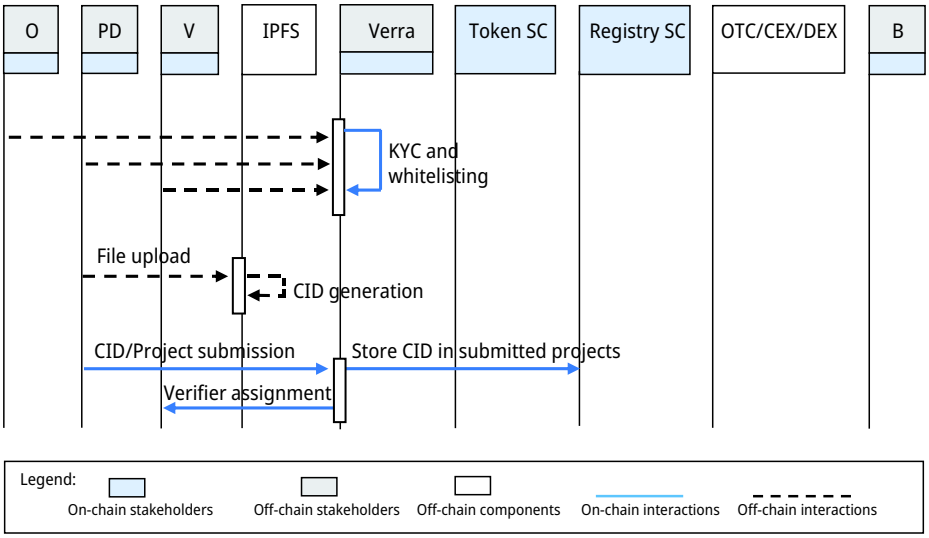

Figure 11.3: Whitelisting and Project Submission.

pants, such as the PD and V, must engage with the standard-setter, like Verra. Once verified, Verra whitelists these participants by linking their blockchain addresses to the Verra SC, granting them access to their role-specific system functionalities. Additionally, since oracles are permitted to provide external data, it is essential to verify the trustworthiness of these data providers. Consequently, for an oracle to be allowed to supply data, it must also undergo verification and it must be whitelisted by Verra as a legitimate off-chain data provider, allowing PDs to select the oracle as needed in the further procedures. After being whitelisted and conducting a feasibility study, PDs can submit their project to Verra. Within the proposed framework, the PD must first upload the project file to IPFS to generate the corresponding CID. Using their blockchain address, the PD can then submit the project through the designated function of the Verra SC by providing the CID as input, which will then automatically communicate the CID to the Central Registry SC for transparency and accountability purposes. This ensures that all submitted projects, regardless of the standard-setter, can be easily accessed and verified. Following submission, a verifier is assigned to the project. This can happen automatically based on predefined criteria or by allowing verifiers to apply for the task. Verra selects the most appropriate method depending on the specific needs and characteristics of the used methodologies.

In the next step, assigned verifiers can use the submitted CID to securely retrieve the project file from IPFS, ensuring a tamperproof transfer. In a typical VCC lifecycle, verifiers manually review the document, assess the project's feasibility, and decide whether to approve its registration.[84] However, the developed concept also allows for the integration of oracles into this process. For instance, PDs can include present and/

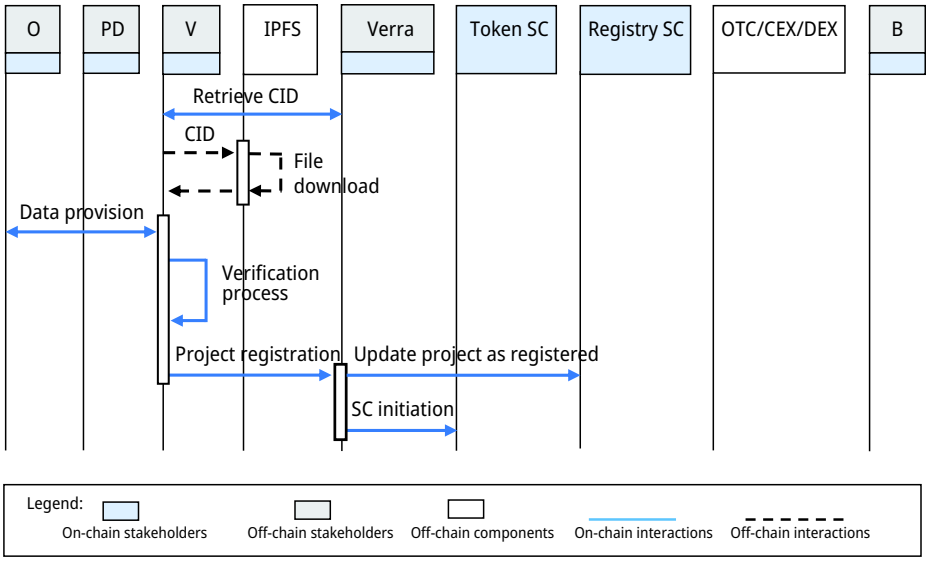

Figure 11.4: Project Registration and Verification.

or historical satellite images of a forest, which demonstrate their efforts to reduce carbon emissions. This integration can enhance efficiency and improve the reliability of the verification process by providing objective, real-time data that complements manual checks, reducing the potential for human error and improving data accuracy. Once verification of the registration is complete, verifiers can use the appropriate registration function to finalise the project's registration. This also triggers two further transactions from the Verra SC: One to the Central Registry SC for adding a new project and one that initiates the Token SC.

In the subsequent phase, PDs are responsible for demonstrating the integrity of their project over its lifecycle. This is achieved by utilising monitoring methods that were determined during the initial phase. These methods may include a variety of techniques, such as satellite imagery or other specific data sources, to track key indicators like carbon sequestration, forest health, or biodiversity levels, depending on the project's goals. PDs must compile these findings into a monitoring report, which is then submitted similarly to the first phase, as shown in Figure 11.4, by uploading it to IPFS and providing the CID to Verra SC. Assigned verifiers can then retrieve the reports and either conduct a manual review or as mentioned earlier, enhance the process by integrating oracles to improve the accuracy and efficiency of the verification. Once the verifiers approve the MRV, the Verra SC automatically notifies the Central Registry SC and updates the token status in the Token SC from pre-issued to issued. Since the report submission and verification are similar to the previous phase, we refer to Figure 11.4 in this phase.

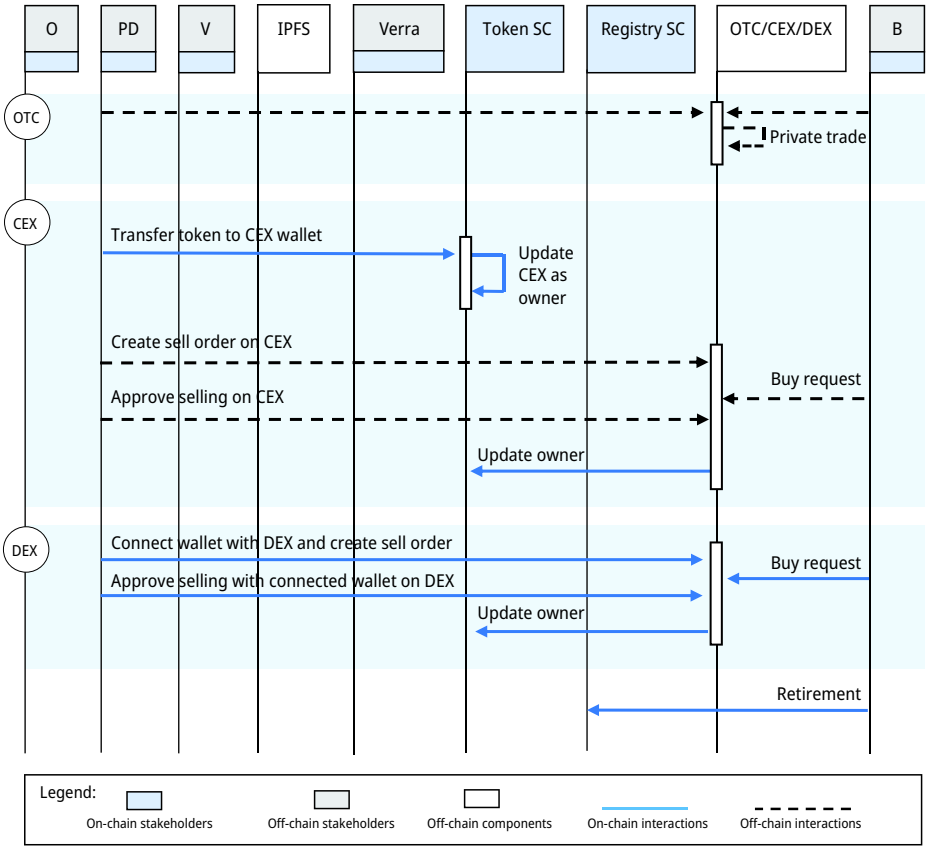

Figure 11.5: Transaction and Retirement.

As outlined in the previous section, token trading can start as soon as the Token SC is initiated. The process remains the same regardless of whether pre-issued or issued tokens are traded or whether it is the initial trade between PD and B or a secondary trade between the current owner and another B. This stage of the VCC lifecycle offers great flexibility, allowing PDs and buyers to select their preferred trading platform and determine how they want to negotiate and process payments. For instance, PD and B can choose OTC trading, where the PD transfers ownership rights directly to the buyer's blockchain address, while payment and negotiation can either happen personally off-chain or on-chain.

Alternatively, they may opt to use a CEX as an intermediary, which provides a regulated environment for transactions. In this case, the PD deposits their VCC tokens into a CEX wallet, meaning the CEX takes custody of the tokens and becomes the registered owner in the Token SC. Once deposited, the PD can trade off-chain within the CEX platform. When a deal is finalised, the CEX updates its internal ledger. After-

wards, the PD can withdraw fiat currency to their bank account, and the buyer can withdraw the tokens. The CEX then updates the Token SC on-chain to transfer ownership to the buyer using the smart contract's transfer function.

Additionally, PDs and buyers can use a DEX for direct wallet-to-wallet trading without an intermediary, using blockchain-native tokens for payment, which makes it the most efficient transaction option. Unlike a CEX, where tokens are held by the exchange, a DEX allows users to retain full control of their assets by trading directly from their wallets. To trade on a DEX, the PD connects their wallet to the platform and creates a sell order through a smart contract. The buyer selects the order, and the DEX automatically facilitates the exchange, transferring tokens directly between wallets on-chain, with the Token SC immediately reflecting the new ownership.

All three options are valid within the system, allowing users to choose based on their preferences. Furthermore, each platform fulfils the necessary regulatory requirements, such as KYC, AML, or CFT, and is therefore not included in the transaction function of the Token SC. Additionally, each option offers thereby varying degrees of transactional privacy. On a DEX, transaction amounts are fully public, while CEX and OTC transactions can keep the transferred amounts concealed. It is, however, important to highlight that blockchain addresses remain visible across all trading options, as ownership is tracked in the Token SC. For traceability and transparency purposes, this visibility is the default setting of the smart contract, but some companies may prefer to obscure their identities for competitive reasons. A challenge with blockchain in this regard is its pseudonymity. While blockchain addresses do not reveal personal details directly, they can still be linked to real-world identities through transaction patterns or external data.[85] However, there are emerging technologies designed to protect user identities, such as stealth addresses or ring signatures.[86] These tools allow users to create unlinkable addresses for increased privacy. However, since these technologies are still evolving and there is no perfect solution yet, it is up to buyers to choose the privacy-enhancing tools that best suit their needs and risk tolerance.

Finally, the last buyer claims the carbon emission reduction by retiring the tokens, using the retire function, which flags the corresponding tokens, making them immovable but still visible for record-keeping. This ensures that the credits are removed from active circulation, thus preserving double spending while maintaining a clear audit trail. Additionally, the retire function allows the buyer to add a comment or metadata, such as a description of what the retired tokens were used for, like financial reporting in a specific year or for a particular project. This added functionality helps the buyer track the purpose of the retired credits, providing a detailed record that can be used for internal reporting, external audits, or regulatory compliance.

6 Evaluation

Since the primary objective of this chapter was to develop a holistic blockchain-based VCC-Lifecycle framework to address several real-world challenges, this section focuses on evaluating its effectiveness by analysing the fulfilment of the defined DOs.[87] To assess how and why the framework meets these objectives, we employ an artificial evaluation approach, leveraging theoretical reasoning to validate the design and establish a foundation for further enhancements.[88]

As outlined earlier, the fulfilment of the *standardisation DO* evolves around the Central Registry SC and its connection with Standard-Setter SCs. Thereby, to enable a seamless connection, the central registry defines key processes that must be standardised by all standard-setters in their smart contracts. This standardisation effort focuses on core functions common to all standard-setters, such as submission and registration. At the same time, the framework offers flexibility, allowing standard-setters to customise specific smart contract functions. This adaptability not only accommodates variations in detailed processes but also lowers entry barriers for participation. Moreover, linking standard-setters to the central registry also enhances the *interoperability DO* by consolidating all participants onto a single platform. This functional integration reduces market fragmentation and fosters a more connected ecosystem.

Additional advantage of the framework comprising of the Central Registry SC, the Standard-Setter SCs, and the Token SCs, is an enhanced visibility within an already transparent blockchain infrastructure. By automatically updating all projects and their corresponding tokens in the registry, the system minimises the opacity commonly found in traditional systems, where information is scattered across multiple platforms, as well as the potential opacity that could arise from having different disconnected smart contracts for various standards on the blockchain. Besides this, the main driver of the fulfilment of the *transparency DO* is, however, the inherent transparency of a blockchain itself, where all transactions are accessible to participants.[89] In this context, transparency means that every transaction, such as project submission or registration, is recorded on a ledger, visible and verifiable by all participants, ensuring no information is hidden.

Moreover, the framework leverages the tamper-resistant nature of blockchain, ensuring that once data is transparently recorded, it cannot be altered or deleted, holding data providers accountable for the integrity of their information.[90] This tamper resistance contributes directly to the *accountability DO* and is primarily achieved through cryptographic hashing. Hashing works by generating a unique 'fingerprint' from the data in each block. Even the slightest change in the data will result in a completely different hash, making any tampering immediately detectable.[91] This is further combined with a decentralised consensus mechanism, which ensures that no single entity can control or alter the blockchain, making manipulation extremely difficult. These characteristics ensure that all data retrieved from oracles or stored on

IPFS becomes tamper-resistant when referenced on the blockchain, even though IPFS and oracles do not inherently provide the same level of infrastructure.

Besides transparency and accountability, the advantages of a blockchain-based infrastructure, combined with the developed framework, also contribute significantly to achieving the *duplication prevention DO* and the *reliable verification DO*. The technology offers a secure method for tracking submitted projects and their progression across various markets within a single, unified location—the Central Registry SC. This unified approach enhances visibility for standard-setters, auditors, and external observers, ensuring comprehensive awareness of all existing projects. Consequently, the risk of double-counting is minimised not only through blockchain's inherent transparency features[92] but also through the framework's construction. Similarly, double-claiming is effectively prevented by leveraging both the technology itself and the linkage of each Token SC to the central registry, enabling participants to track existing tokens, the projects they represent, and their current status.[93] Beyond duplication prevention, the framework also enables traceability in the project verification process, allowing stakeholders to review and audit the steps involved in the typically opaque MRV process. While verification remains largely performed by third-party entities, the integration of oracles, which provide trustworthy off-chain data signed using cryptographic keys, significantly improves the validity of project information by reducing reliance on data submitted solely by PDs.[94]

Furthermore, oracles not only enhance the verification process but also play a key role in achieving the *operational efficiency DO*. By integrating oracles into smart contracts, the system can automatically retrieve relevant data for verification, significantly improving speed and enabling thresholds for automated checks. For example, smart contracts can be programmed to automatically verify whether a forest has grown in a predetermined area based on data provided by oracles. This capability underscores automation as one of the core strengths of smart contracts, enabling the seamless execution of processes with precision and efficiency.[95] Beyond their use with oracles, this automation extends to several standardised functions, such as the creation of Token SCs and the automatic reporting of projects to the Central Registry SC. By automating these processes, the framework reduces reliance on manual operations, minimising human errors and improving overall functional efficiency.[96] Additionally, the flexibility of the Standard-Setter SCs allows them to incorporate further automation into their processes as needed, enabling even greater efficiency.

The *transactional efficiency DO* is also supported by automated processes, such as the automatic update of ownership after tokens are sold. However, the primary driver of transactional efficiency lies in the reduced or eliminated involvement of financial intermediaries in the trade process, depending on the chosen trading platform.[97] As a result, transactional efficiency is inherently tied to the flexibility of platform choice. For example, if a seller and buyer decide to use an OTC platform or a DEX for trading, they eliminate the need for financial intermediaries,[98] which often create entry barriers in a regular VCC lifecycle through high transaction fees and slow processes, ulti-

mately reducing efficiency.[99] In contrast, trading on a CEX involves financial intermediaries, which may reduce transactional efficiency. Nonetheless, using a CEX must remain an option to ensure inclusivity, particularly for participants who do not own the native cryptocurrency and prefer trading on platforms that accept fiat currencies or offer advanced custodial services, like a CEX.

The different trade platforms also support *the trade-specific aspects of the participant identification DO*, besides the *VCC-specific aspects*, which are achieved through the whitelisting procedures implemented by standard-setters and their smart contracts at the initial stage. These identification processes are essential for meeting regulatory requirements such as KYC, AML, and CFT compliance.[100] While standard-setters address the regulatory requirements for the VCC market, each trade platform implements participant identification in its own way to comply with trade-specific regulatory obligations.[101] For instance, CEXs inherently require all participants to identify themselves as part of their operational model. This allows the exchange to conduct KYC checks, monitor transactions, and ensure compliance with AML and CFT regulations. In contrast, platforms like DEXs or blockchain-based OTC trades often rely on external mechanisms for compliance, including the use of CEXs for identity verification.[102] Some DEXs also integrate smart contract-based KYC or AML verification, requiring users to complete identity checks before accessing specific trading functionalities.[103] These advancements enhance compliance while preserving the decentralised nature of these platforms. Furthermore, for OTC transactions conducted outside blockchain-based mechanisms, regular bank accounts provide a practical alternative. They apply standard KYC and AML processes enforced by private banks, ensuring the same level of regulatory compliance.

Finally, the achievement of the *privacy DO* is also closely linked to the selection of the trading platform. As outlined earlier, privacy in this context consists of two aspects: privacy of the transaction amount and identity privacy. On DEXs, transaction amounts are fully visible, while CEXs and OTC trades can obscure this information. However, blockchain addresses remain publicly visible regardless of the platform, as they are tracked within the Token SCs. While the addresses themselves do not directly reveal the real identity behind them, they can potentially be linked to real-world identities through clustering techniques that analyse transactional patterns.[104] This pseudonymity is an intentional feature of the framework, designed to balance privacy with the transparency and traceability benefits discussed earlier. Nevertheless, technologies such as stealth addresses and ring signatures, offer the potential to enhance the privacy DO by enabling unlinkable addresses and providing stronger protection for user identities.[105] Yet, as these tools are still evolving and no perfect solution currently exists, users must independently select additional privacy-enhancing measures that best align with their individual privacy needs and preferences.

In conclusion, the holistic blockchain-based VCC lifecycle framework addresses several inefficiencies and challenges inherent in the traditional VCC lifecycle by fulfilling the defined DOs and offering stakeholder-specific flexibility. Additionally, for this

framework to function effectively, it provides strong incentives for different stakeholders to participate. Standard-setters, for instance, can be attracted by the enhanced visibility of their services to potential project developers and offset buyers, while increasing efficiency and retaining their unique specifications through the flexibility offered by the framework. Additionally, project developers and buyers holding VCCs at different stages of their lifecycle benefit from the inclusion of DAO governance functionality of the Central Registry SC. This feature incentivises participation by promoting fairness and granting stakeholders greater influence over market governance. In summary, the framework not only addresses inefficiencies in the traditional VCC lifecycle but also fosters a collaborative and transparent ecosystem where all stakeholders are empowered to contribute meaningfully, ensuring the long-term sustainability and scalability of the VCC market.

7 Discussion and conclusion

VCCs play a notable role in global efforts to combat climate change, providing a mechanism for offsetting carbon emissions while driving investments in sustainability and innovation. However, the effectiveness of VCCs is undermined by persistent challenges such as the lack of verifiability, transparency, and trust.[106] These issues hinder the credibility of the VCC market and limit its potential to deliver genuine environmental benefits. In this discussion, blockchain-based tokenisation of VCCs is often highlighted as a promising solution to address key challenges, owing to its inherent characteristics like transparency and tamper resistance. Building on this foundation, our research explores the potential of blockchain combined with complementary technologies such as decentralised file systems and trusted oracles to design a robust and reliable holistic VCC token framework.

This process was guided by the DSR methodology.[107] After identifying DOs for all VCC-lifecycle phases through a thorough literature review, we developed a holistic framework that was refined through an iterative cycle of evaluation and improvement, ensuring its practical applicability and effectiveness. At its core, the framework integrates key stakeholders through a set of interconnected smart contracts: the Standard-Setter SC, the Token SC, and the Central Registry SC. These contracts together mirror the essential lifecycle processes, such as project submission, verification, token issuance, and retirement. Thereby, the Central Registry SC acts as the central connecting hub for all standard-setters, enhancing transparency and traceability across all participants and preventing issues like double-counting through standardised reporting and registration. Complementing the blockchain infrastructure, the framework incorporates off-chain components, such as IPFS for decentralised storage of project-related documents, and oracles to bridge the gap between the blockchain and external data sources. In addition, the framework supports multiple trading options, including

OTC, CEX, and DEX, allowing participants to select their preferred methods based on their individual needs. Finally, the concluding evaluation demonstrates that the proposed blockchain-based VCC lifecycle framework effectively fulfils the defined DOs, addressing challenges related for example to standardisation, transparency, accountability, and efficiency.

Yet, although the concept offers a feasible solution to the primary challenges associated with VCCs, several technological, regulatory, and business-related aspects remain open and require further exploration and refinement. One key consideration is the choice of blockchain type for implementing the proposed design. We advocate for a highly transparent solution, such as a public permissionless blockchain like Ethereum, to maximise transparency and security.[108] However, public blockchains often face scalability challenges, leading to slower processes and increased costs, which could negatively impact both operational and transactional efficiency.[109] Considering these limitations, public permissioned blockchains may offer a more practical alternative by addressing scalability concerns.[110] However, this approach introduces trade-offs in decentralisation, as permissioned blockchains restrict participation through predetermined rules, potentially limiting openness.[111] Another viable solution could involve employing a public permissionless blockchain in conjunction with scalability-enhancing technologies such as rollups, which process transactions off-chain to improve efficiency.[112] While promising, these technologies are still in their early stages and often raise additional questions that require further evaluation. Given these complexities, our research has deliberately focused on developing a conceptual framework rather than specifying a particular technological implementation. By prioritising the conceptual view, we aimed to establish a flexible foundation that enables a more detailed technological analysis in the future.

Furthermore, several questions regarding the appropriate business implementation remain unresolved and warrant further research, particularly in the development of viable business models that effectively address cost and revenue structures. These models are essential to ensure the long-term sustainability of such designs. For example, it remains unclear how costs associated with blockchain transactions, such as gas fees, will be managed and fairly distributed among stakeholders. Equally critical is determining how revenue streams will be structured, whether through transaction fees or subscription-based services. Additionally, the framework's flexibility to accommodate diverse stakeholders, including standard-setters, project developers, verifiers, and buyers, necessitates a clear definition of their roles and financial responsibilities within the system. The inclusion of complementary technologies, such as oracles and decentralised file systems, further complicates the cost structure, introducing additional expenses that must be integrated into the business model. Addressing these considerations, which are strongly interconnected with technology choices, is crucial for creating a financially sustainable and equitable framework that aligns stakeholder incentives with operational efficiency.

Beyond the technical and business considerations, the developed design must also remain adaptable to evolving regulatory landscapes. As a relatively new technology, blockchain continues to be the focus of dynamic regulatory discussions at both national and international levels. While the proposed framework incorporates key regulatory requirements, a more detailed legal analysis will be necessary to refine and adjust the smart contracts to specific jurisdictions. In conclusion, the presented design provides a strong foundational framework for addressing the most pressing challenges in the VCC market. However, unlocking the full potential of this framework will require addressing the remaining questions and refining its components through collaborative effort and continuous adaptation. With further exploration, this design has the potential to play a key role in establishing a transparent, efficient, and trustworthy VCC ecosystem that aligns with global sustainability goals.

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