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6 From project design to retirement: The role of blockchain along the voluntary carbon credit lifecycle

Abstract: The emerging topic of Voluntary Carbon Credits (VCCs) showcases the rapid evolution of a broad spectrum of practical and theoretical concepts. However, this environment entails practical projects with short lifespans as well as the absence of clear and established standards and best practices for the technical concepts and foundations of VCCs. Against this backdrop, we survey and discuss blockchain-based theoretical concepts and technical implementations for VCCs as well as the potentials and challenges of existing approaches based on academic literature and practical use cases. Thereby, we aim to identify best practices as well as pitfalls of existing practical implementations and theoretical concepts and lay the foundation for a standardised technical VCC implementation that can successfully foster a broader adoption and practical diffusion.

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

1	Introduction —	133
2	Background —	135
2.1	Blockchain and tokenisation —	135
2.2	Voluntary carbon credit lifecycle —	136
3	Operational approach —	137
4	Results —	138
4.1	Blockchain application possibilities —	139
4.2	Value proposition of blockchain for VCCs lifecycle steps —	142
4.3	Additional requirements —	143
5	Discussion and conclusion —	145

1 Introduction

The pressing global challenges posed by climate change and environmental degradation have propelled the need for effective solutions, as evidenced by the Paris Agreement and the United Nations' Sustainable Development Goals (SDGs).¹ This collective commitment emphasises the critical importance of environmental sustainability in shaping a viable future for all. In this context, the development of alternative solutions that contribute to solving the climate challenges outlined in the Paris Agreement is essential. For instance, Voluntary Carbon Credits (VCCs) are frequently highlighted as a prominent

solution for reducing carbon emissions globally.² However, VCC providers and their solutions are facing several challenges when striving to adopt their solution into practice broadly. Current challenges that need to be overcome with VCC solutions on the market include a lack of standardisation, complexity, and opacity in processes related to their creation, transfer, and verification. This lack of standardisation leads to inconsistencies and uncertainties regarding the structure and functionality of VCCs, complicating participation for businesses and investors as well as undermining trust in the market.³

Furthermore, verification of the actual climate mitigation efforts represented by VCCs can be challenging and may require time-consuming and costly procedures, affecting market efficiency. Additionally, limited integration and interoperability with existing climate mitigation initiatives or markets can diminish the effectiveness and acceptance of VCCs among various stakeholders. Market volatility caused by supply and demand dynamics, as well as external factors like political decisions and economic trends, contribute to the unpredictability and instability of the VCC market.⁴ Moreover, there is a risk of misuse and misconduct, such as greenwashing, where companies make misleading or inaccurate claims about their environmental performance to enhance their image. For instance, this has recently occurred in China, where many already existing facilities in China were submitted as supposedly newly constructed Upstream Emission Reductions (UER) projects in Germany, some without the knowledge and approval of the Chinese owners.⁵

Addressing these challenges requires a careful examination of existing VCC solutions and the implementation of measures to enhance transparency, verifiability, integration, and governance in the market. Blockchain technology, particularly through tokenisation, holds the potential to mitigate these challenges. By leveraging blockchain's decentralised and immutable nature, tokenisation can enhance transparency, traceability, and auditability in VCC transactions, thereby reducing the risk of fraud and enhancing trust among market participants. Furthermore, blockchain-based tokenisation can facilitate seamless integration and interoperability between VCC platforms and existing climate initiatives or markets, fostering greater efficiency and effectiveness in climate mitigation efforts.⁶

In the landscape of sustainability research using blockchain technology, research studies primarily focus on the design and implementation of blockchain solutions for various environmental applications. However, there exists a conspicuous absence of research examining the broader value propositions that blockchain technology offers specifically for VCCs throughout their lifecycle stages. While individual studies may provide insights into specific aspects of VCC design or blockchain implementation, a holistic understanding of the overall value propositions of blockchain technology in this context remains elusive.⁷ This research gap highlights the need for a systematic and particularly technical analysis of the potential benefits and challenges that blockchain technology presents across the entire lifecycle of VCCs, from issuance to retirement of VCCs.

Therefore, the objective of this book chapter is to investigate the value propositions that blockchain technology provides for addressing technical requirements in

the design of VCC solutions, considering the various stages of the VCC lifecycle. By examining the unique features and capabilities of blockchain technology in facilitating transparent, secure, and efficient VCC transactions, this study aims to investigate how blockchain can contribute to the advancement of sustainable practices in carbon credit markets. Concretely, this book chapter strives to answer the following research question:

RQ: What value propositions does blockchain technology provide for addressing technical requirements when designing voluntary carbon credit solutions considering the VCC lifecycle stages?

Through a comprehensive analysis of existing literature, practical case studies, and theoretical frameworks, this research seeks to provide valuable insights for policy-makers, practitioners, and researchers alike, ultimately contributing to the development of more effective and sustainable solutions for addressing climate change by reducing carbon emissions.

The remainder of this chapter is structured as follows. Section 2 outlines the theoretical background of blockchain technology and tokenisation, as well as a detailed description of the VCC lifecycle. Section 3 presents the methodology used, while section 4 highlights the results, emphasising blockchain's value propositions at various stages of the VCC lifecycle. Lastly, Section 5 engages in a discussion of these findings, addressing their implications for the market and technology adoption, and concludes with recommendations for policymakers and practitioners.

2 Background

2.1 Blockchain and tokenisation

In recent years, blockchain technology has emerged as a transformative force reshaping various industries. Functioning as a distributed ledger technology (DLT), blockchain operates within a peer-to-peer network, replicating and synchronising data across multiple nodes to ensure fault tolerance and decentralisation.⁸ Its operation relies on public key cryptography to facilitate secure and transparent transactions, executed through a consensus protocol operated by specific nodes.⁹ At its core, blockchain utilises an append-only structure in which transactions are grouped into blocks and linked together using hash pointers to form a tamper-proof chain.¹⁰ Each block contains the hash of its predecessor, ensuring the ledger's integrity and immutability, thereby eliminating the need for a central authority, and mitigating the risk of a single point of failure, fostering trust among participants.¹¹ For instance, this can be illustrated with examples from the cryptocurrency domain, where blockchain technology underpins systems such as Bitcoin and Ethereum, ensuring secure and transparent transactions. Furthermore, tokeni-

sation can be implemented using various technologies, with blockchain providing an effective solution for enhancing transparency and efficiency.

Tokenisation, a prominent application of blockchain, entails representing real-world assets as digital tokens on the blockchain. These tokens democratise access to assets, enable fractional ownership, and facilitate faster and more efficient transactions.¹² Using smart contracts, programmable agreements encoded on the blockchain, tokenisation automates processes such as dividend payments and compliance management, thereby enhancing efficiency and transparency.¹³ The convergence of blockchain and tokenisation heralds a new era of innovation and disruption, redefining traditional paradigms of ownership and finance. As these technologies continue to evolve, their impact on finance, commerce, and society is expected to be profound, promoting decentralisation, efficiency, and inclusivity. An illustrative example of this is the tokenisation of company shares through the creation of digital tokens on a blockchain, each representing a fractional ownership in the company. These tokens can subsequently be sold to investors via a Security Token Offering (STO). Trading these tokens on blockchain-based exchanges offers several advantages, such as increasing market accessibility, enhancing liquidity by enabling 24/7 trading, providing additional transparency and security due to the immutability of the blockchain, and reducing costs by eliminating intermediaries such as brokers and clearinghouses. With the described potential and the rising importance of carbon neutrality in combating climate change, tokenisation presents a powerful tool for scaling the use of VCCs. In summary, by creating digital representations of carbon credits on a blockchain, tokenisation can streamline trading, improve traceability, and unlock new market opportunities, driving greater efficiency and accessibility in the growing carbon credit market.

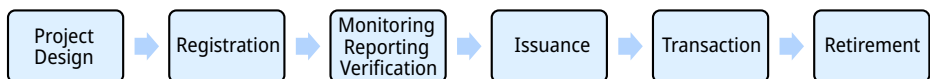


Figure 6.1: VCC Lifecycle Stages.

2.2 Voluntary carbon credit lifecycle

The life of a VCC can be divided into six stages¹⁴ as illustrated in Figure 6.1. The first stage is the *project design*. Initially, the project developers have to conduct a feasibility study and select an accredited standard for quantifying emissions.¹⁵ A feasibility study in this context involves evaluating the technical, economic, and environmental viability of the project, ensuring that it can effectively reduce carbon emissions as intended. It includes assessing the potential environmental impact, costs, benefits, and overall practicality of the project.

Since project designers must submit their design for *registration* under a selected standard in the next step, they typically align their design with the standard's require-

ments to facilitate approval. The standard in the VCC context refers to a recognised framework or protocol that sets the criteria and methods for measuring, reporting, and verifying the emissions reductions achieved by the project. These standards aim to ensure that the carbon credits generated are credible, consistent, and can be trusted by buyers and regulators. Examples of such standards include Verra, the Gold Standard, Climate Action Reserve, and the American Carbon Registry. To ensure the robustness and reliability of these standards, independent experts conduct comprehensive assessments and verifications.

The project registration is finalised upon approval by the standard setter, which provides project developers with frameworks and guidelines to quantify and certify emission reductions during the subsequent *monitoring, reporting, and verification (MRV)* processes, ensuring verifiable carbon emission compensation.¹⁶ Since project developers are responsible for monitoring emission reductions themselves, the reliability of the project depends on the accuracy of the reported data. Consequently, during this stage, project developers must contact third-party auditors to ensure the accuracy of their claims.¹⁷

After the MRV processes have successfully finished, the next step is the *issuance* of the corresponding credit by the standard to the project developers. When issuing the credit, it is important to represent the VCC and its ownership digitally and rightfully, which means accurately reflecting ownership and ensuring compliance with established standards and protocols in the issuance and transfer process.¹⁸

Following issuance, the VCC can be sold on the market, initiating the *transaction* phase. Usually, this will be either done through offtake agreements (contractual arrangements between a producer of goods or services and a buyer), through brokers or other intermediaries that resell the credits, or through exchanges that offer buyers a platform to access potential credits.¹⁹

The final stage is the *retirement* of the VCC. This generally happens through the final buyer claiming the environmental benefits. During this stage, the credit is permanently removed from the market and is no longer available for transaction, thereby eliminating the risk of double-spending, which refers to the fraudulent use or claiming of the same credit by multiple parties.²⁰

3 Operational approach

To answer our research question, we first aimed at conducting a structured literature review.²¹ After an initial, explorative search and testing of different keywords, we derived our final search string ('blockchain' OR 'DLT' OR 'distributed ledger' OR 'tokenisation') AND ('carbon' AND ('credits' OR 'markets' OR 'offsets')) and applied it to a broad palette of academic databases, namely Science Direct, IEEE Explorer, AIS eLibrary, ACM Digital Library, and Web of Science. However, from backward and forward searches, we realised the importance of grey literature, that is, non-peer-reviewed literature, in

this research stream. Thus, we also incorporated grey literature that we encountered through forward and backward search applied on our white literature and a Google Scholar search.²² However, even with grey literature, our dataset remained insufficient and incomplete. Thus, we decided to only focus on a detailed investigation of the seminal works collected in our review supplemented with an examination of real-world examples. Furthermore, we draw upon literature from other blockchain applications that present application patterns and knowledge that are transferable to the application of VCC tokenisation.

4 Results

To understand the value propositions that blockchain can offer in the VCC context, we first outline the various ways blockchain can be applied to the overall process or specific steps. These applications are gathered from real-world examples, current VCC literature, or transferred from other BC applications. Subsequently, we abstract the underlying value propositions of blockchain technology for these specific application possibilities and VCCs in general. Finally, we identify additional, more specific requirements for the design of the blockchain system that must be met to fully leverage the value propositions of blockchain for VCCs. An overview of these value propositions is illustrated in Table 6.1.

Table 6.1: BLC Value propositions in the VCC context.

	Step 1 Project Design	Step 2 Registration	Step 3 Monitoring, Reporting, Verification	Step 4 Issuance	Step 5 Transaction	Step 6 Retirement
Blockchain application possibilities	Committing on a certain project design (including governance and registration) through storing respective data on the blockchain	Committing on reported data		Digital representation of the VCC and its ownership Transfer of ownership		Retirement on the blockchain
		Incorporating trusted oracles with signed data		Transparent markets		

Table 6.1 (continued)

	Step 1 Project Design	Step 2 Registration	Step 3 Monitoring, Reporting, Verification	Step 4 Issuance	Step 5 Transaction	Step 6 Retirement
			Automatable Verification according to transparent rules			
	Setting up a DAO that governs the respective processes					
Value proposition of BC for VCCs lifecycle step	Immutability/tamper proof					
	Accessibility in public blockchains/transparency					
	Decentralisation/independency from verified third party					
Additional requirements	Verifiability of data origin			Identifiability of owners		
	Selective information sharing			User/owner privacy		
	Ensuring liquid markets					

4.1 Blockchain application possibilities

The life of a carbon credit initially begins with selecting a specific *project design* and registering it under an *accredited standard* and afterwards, *monitoring, reporting, and verifying* the data, enabling the creation of VCCs.²³ All three tasks involve providing reliable information and commitments that must be maintained to ensure the validity of the later-minted credits. By posting this information on a blockchain, it becomes publicly visible and immutable, allowing others to hold the project designer accountable for the information provided. Alternatively, instead of posting all the information, one might post only a hash of the data on the blockchain and provide the remaining information off-chain. This approach still ensures the immutability and verifiability of the data while reducing the load on the blockchain and associated costs. If fully disclosing information might compromise data sensitivity, one might just post the hash of the information on the blockchain but refrain from providing the information itself off-chain upfront. While this would not provide public visibility and verifiability of the information, its immutability would still be secured, e.g., as in the case of a dispute where a project designer is forced to reveal project information, it could be checked whether this information matches the hash that was published on the blockchain. This approach is also used by the Regen Network to ensure the trustworthiness of the collected data.²⁴

Another possibility of applying blockchain technology, specifically during *monitoring and reporting* of the VCC lifecycle, is to incorporate trusted oracles responsible for monitoring and reporting the data that can use cryptographic keys to sign the data and ensure its authenticity and traceability. This approach is, for example, already being proposed when it comes to tracing carbon emissions in the electricity sector.²⁵ Here, similar to VCCs, a core challenge lies in ensuring the validity and integrity of the primary data, such as the amount of carbon emitted during electricity production, or the amount of carbon actually captured during project design. To address this, the integrity of metering devices is periodically verified and then attested to the metering devices through a digital certificate issued by a trusted agent, either directly from a regulatory body or a company certified by such a body. This allows the data reported to the blockchain to be signed with a cryptographic key by the metering devices and appended with the certificate, ensuring that the data was reported by a certified device and has not been altered. Additionally, using hardware security modules (HSM) can further ensure the binding of the certificate to the metering device. The electricity sector benefits from an already established network of sensors, such as smart meter gateways, which can report this data. This task is more complex for VCCs. However, even if only some of the relevant information would be reported like this, for example, using satellite data, signed by the respective satellite to ensure data authenticity, it would already be progress compared to fully untraceable reporting. This approach is, for example, already being used by CarbonStack by creating more transparency for its projects using satellite observation and blockchain technology.²⁶

Due to its transparent rules and the possibility offered by smart contracts, blockchain technology could also facilitate automated *verification*. Carbon standard providers could implement some of their verification criteria on the blockchain in the form of smart contracts. This would offer two main benefits: Firstly, the data reported by the project, which was posted on the blockchain in the previous step, could be processed automatically. Secondly, the rules underlying the verification and their enforcement would be conducted transparently, reducing the level of trust required in the standard providers. Certainly, this approach would be highly specific to the concrete use case and would require the implementation of complex verification rules, thereby complicating the integration of all necessary information into smart contracts. However, even if it is not feasible to encode every detail on the blockchain, establishing a fundamental set of rules could significantly enhance the transparency of the process. Until now, carbon credits (VCCs) have not been efficiently translated into smart contracts, even though there is a significant potential for enhancing transactability and standardisation.²⁷

Although stages one to three present multiple opportunities for blockchain to enhance transparency, verifiability, and data immutability, in the current VCC market, trusted third-party verifiers are predominantly employed and relied on to ensure the integrity of the information provided, monitored, and reported, and the verification processes that form the first three steps of the VCC lifecycle.²⁸ When it comes to stages

four to six, which will be discussed next, however, blockchain technology already finds application in various ways in today's VCC practice.

Before a VCC can be purchased, it must be *issued* by the standardisation organisation by adding a respective entry in their VCC register. Blockchain can either be incorporated in this step by transferring the VCC register of the standard provider natively on the blockchain or leaving the existing register unchanged and just representing the ownership to specific entries in this register through tokens on the blockchain. Both of these options offer the advantage of immutable records for token transactions and ownership.²⁹ Additionally, the publicly visible documentation could also counteract the problem of double-counting measurements that are legally required, that is, issuing VCCs for actions that are already obligatory. Only if it is ensured that projects financed through credits do not ultimately displace governmental climate protection measures can one truly speak of 'compensation'.³⁰ In the first approach, the entire VCC register maintained by the standard provider is migrated to a blockchain-based system. Each issuance of a VCC and subsequent transactions are recorded directly on the blockchain ledger. This method leverages blockchain's inherent properties, such as immutability, transparency, and decentralised consensus mechanisms, to establish a tamper-proof record of VCC ownership and transaction history. By decentralising the VCC register, this approach reduces the risk of data manipulation or unauthorised access, ensuring that stakeholders can verify the authenticity and ownership of VCCs reliably through transparent blockchain records. Alternatively, blockchain technology can tokenise specific entries within the existing VCC register maintained by the standard provider. Instead of migrating the entire register, ownership of VCCs is represented by digital tokens on the blockchain. Each token corresponds to a specific entry in the traditional VCC register, indicating ownership and enabling transparent tracking of ownership transfers on the blockchain platform. This approach is more widespread today as it does not require the direct change of the register infrastructure by the standardisation organisation itself. However, as a result, it introduces a possible vulnerability in the form of another oracle problem instance. It must be ensured that the ownership of the token properly represents ownership of the underlying VCC, that is, that the token represents a righteous VCC and that the ownership of the VCC cannot be transferred independently from the token. An illustrative instance can be observed in the initial implementation of the Toucan Protocol, where VCCs were retired before the process of tokenisation. Consequently, the tokens created within this framework represented VCCs that had already been retired.³¹

After the VCC is represented on a blockchain, the blockchain can also be used to facilitate *transaction* of the VCC. This process, along with the publicly visible record, enables robust accounting practices that prevent ambiguity over ownership and double-counting of emissions reductions.³² The use of blockchain technology also enhances the transparency of trading and, consequently, the markets.³³ This can facilitate open access to trading platforms, making markets more accessible to the general public. However, while technically feasible, the transfer of tokens between different

blockchains that is necessary to maximise this openness still presents a hurdle that often introduces intermediaries responsible for operating the respective bridges between the blockchains. One example is the Toucan Protocol, which acts as a central intermediary with the aim to facilitate the onboarding to and bridging between many different blockchains.³⁴

The final step of the VCC lifecycle is its *retirement*, which occurs when the environmental benefit has been claimed by the final buyer. During this phase, the credit is permanently removed from the market and is no longer available for transactions.³⁵ This is achieved by deactivating the credit on the blockchain, rendering it unusable. Retiring the VCC on the blockchain offers the same advantages mentioned previously: It ensures there is no double-counting and that environmental benefits cannot be claimed multiple times. The Moss MCO2 Token, for instance, employs a Verra registry to provide proof of retirement.

One more possible blockchain application that is not focused on a specific step but can instead be applied to the *whole VCC lifecycle* is establishing a Decentralised Autonomous Organisation (DAO) to govern the respective processes. Doing that could help to automate processes and make them more transparent, as they are guided by a fixed set of rules set by the DAO, for example, in the form of smart contracts. However, as evidenced by the case of Klima DAO, DAOs may encounter limitations when interacting with stakeholders outside the crypto world. This challenge compounds the significant barriers posed by the adoption of novel technology (blockchain), which may not seamlessly integrate with numerous processes external to the crypto sphere.³⁶

4.2 Value proposition of blockchain for VCCs lifecycle steps

In the previous section, specific blockchain applications for the VCC lifecycle were presented. These applications leverage a set of fundamental value propositions of blockchain technology that will be highlighted in the following section.

One of the main perks of using blockchain technology is that the data on the blockchain is immutable and therefore tamper-proof. This is especially important when *committing to data*, as it ensures that the data cannot be tampered with afterwards and can be trusted for its validity. Its unchangeable nature and publicly visible record also enable robust accounting practices that prevent ambiguity over ownership and double-counting of emissions reductions.³⁷ This provides the advantage of bringing transparency to the history of an asset, such as an In-Transit Money Order.³⁸ Once the token is created, the *ownership* of the credit will also be thoroughly documented, preventing double-spending and reducing the risk of credit theft. Additionally, it ensures that the credit cannot be reactivated after *retirement*.

In addition to recording its history, blockchain technology generally enhances data transparency. Tokenising VCCs strengthens transaction security and traceability while improving their composability by embedding these digital assets more deeply

into the blockchain ecosystem.³⁹ Although VCCs are digital certificates verifying that one ton of CO₂ emissions was avoided by a company or environmental project, the credibility and verifiability of these claims on current exchanges fall short of the transparency that public visibility on a blockchain can provide.⁴⁰ Blockchain can effectively address the challenge of limited transparency in the verification process, thereby supporting a transparent and high-quality voluntary carbon market.⁴¹ Importantly, the integration of contracts into the blockchain establishes intrinsic self-regulation, such as IT governance, transparency, security, and self-custody, which significantly enhances the credibility and quality of the global carbon credit system.⁴² Specifically, this enables the integration of smart contracts into the VCC system. For instance, data can be verified through technologies such as satellite imagery, making it transparent to all participants. Additionally, the market price of VCCs can be monitored, ensuring the fairness of the system by preventing the sale of VCCs to different individuals at varying prices.

Finally, blockchain offers the possibility of decentralised data storage and a decentralised consensus on future transactions, thus eliminating the dependency on and control over the system of individual third parties. This ensures the availability and the integrity of the data. By storing the data on multiple nodes, no single entity has to trust the other regarding the validity of the information. This mitigates the issue of needing a universally trusted party, which is particularly challenging on a global scale. This advantage is present at each stage of the VCC lifecycle, but the integrity is particularly crucial during steps four to six as the information related to the purchase and retirement history of the VCC is stored.

4.3 Additional requirements

After presenting possible uses of blockchain and highlighting the underlying value propositions, there are still additional requirements and aspects that must be considered to enable a holistic implementation.

Although data becomes completely transparent and immutable once it is placed on the blockchain, there is a challenge in validating the data before it is uploaded. This can be addressed, as proposed above, by using smart contracts to help autonomously monitor the data which, however, needs to be reported by an oracle. Thus, while the verification through the smart contract is trustless and autonomous, there is a challenge in measuring the data used, depending on the carbon-saving project, which still requires trust in the onsite data collection and verification. Then, a trusted third party (such as a verification office) is needed to validate the data before it is uploaded to the blockchain. One could argue that the necessity of a trusted third party at this step could undermine one of the main advantages of using blockchain for VCCs in general: the elimination of the need to trust a specific authority, thereby enabling global trading. This can be problematic if the data uploaded to the block-

chain is already faulty. In such cases, while the blockchain will ensure that the data is transparent and immutable, it does not guarantee the validity of the data simply by virtue of being on the blockchain.

Even though transparency is particularly advantageous in the context of VCCs and is considered a means to address existing problems, it can also be detrimental or excessive, posing the question of whether it is necessary to share all information publicly. Maintaining private communication among internal contributors helps safeguard proprietary information and strategic discussions within the blockchain framework.⁴³ If the fully transparent storage on the blockchain makes sensitive data accessible to everyone, it would be unavoidable to consider implementing a mechanism for selective disclosure. This would involve a more precise selection of the data that is transparently stored on the blockchain and the data for which only a hash or similar representation is stored. The tension between transparency and data privacy in blockchains arises from the need to balance the public accessibility of transaction data, which enhances traceability and verifiability, with the protection of user privacy, which can be compromised by the deanonymisation of pseudonymous transactions through various forensic analyses.⁴⁴ This duality poses a challenge as it necessitates the development of identity systems that can provide the benefits of traceability and verifiability enabled through transparency without compromising on data privacy and user security.⁴⁵ The trade-off between transparency and traceability of information and data protection is also relevant regarding the identifiability of owners. The issue of privacy must be addressed, as it often contradicts the identifiability of the owner and the transparency of the transaction. For many parties, it is important – or even legally required due to regulations such as Know Your Customer (KYC), Anti-Money Laundering (AML), Countering the Financing of Terrorism (CFT), or the Supply Chain Act – that they know with whom they are interacting. Blockchains, by default, are pseudonymous. Participants only know the addresses involved in transactions, not the actual identities behind those addresses. Therefore, it is necessary to have a mechanism to identify these parties, either directly on the blockchain or off-chain and then only allow addresses that have been verified.

In steps four to six, the ownership and trading of tokens would effectively take place on the blockchain and thus be openly visible. However, this transparency can be problematic for various reasons: Users may not want their transactions to be public, companies may fear for the confidentiality of their business secrets, particularly concerning their balance sheets, and there may even be legal issues such as compliance with the General Data Protection Regulation (GDPR). Therefore, it is essential to ensure that interactions and transactions comply with relevant legal and regulatory requirements while maintaining the advantages of blockchain technology. Balancing transparency with privacy is crucial because it ensures that sensitive personal information remains secure while allowing essential transaction details to be transparently communicated through multiple channels.⁴⁶ Therefore, an important challenge

is to determine how to implement steps four to six on the blockchain without violating privacy.

The primary idea behind implementing the transaction of the VCCs on the blockchain is to ensure inclusivity in the system. By leveraging the openness of the blockchain, all individuals can participate in token trading. Accessibility is vital because it promotes fairness and inclusivity, allowing a broader range of participants, including smaller entities and individual investors, to engage in trading activities. Blockchain technology can enhance market accessibility by eliminating barriers such as geographical restrictions, reducing reliance on intermediaries, and enabling direct peer-to-peer transactions. Additionally, fractionalisation allows even those with smaller sums to engage in the market, while disintermediation can reduce transaction costs.⁴⁷ This democratisation of access can also foster innovation, competition, and efficiency within the market ecosystem. However, these theoretical advantages are rendered ineffective if the market lacks sufficient liquidity, as this results in inefficiency and deters participation. To fully realise the potential benefits, it is crucial to create incentives or establish collaborations that enhance market liquidity, particularly during the bootstrapping phase when the market is just being established and activity is minimal.

5 Discussion and conclusion

The affordances of blockchain technology exhibit a strong fit to the contemporary challenges faced by VCCs, particularly regarding transparency, verifiability, and the removal of intermediaries and central authorities necessitating trust. Its application spans a wide array of use cases across the entire VCC lifecycle. This includes recording the initial project design on the blockchain, reporting data through the blockchain, tokenising and trading VCCs, and ultimately retiring the tokens along with the associated VCCs. However, despite the evident strong alignment between blockchain capabilities and the challenges faced by VCCs, blockchain alone is insufficient to address all VCC challenges comprehensively. While blockchains can guarantee verifiability and integrity for data that is natively stored on them,⁴⁸ they fall short in fully ensuring the verifiability and integrity of off-chain data, that is, information that first needs to be onboarded to the blockchain by oracles.⁴⁹ However, in the context of VCCs, the integrity and reliability of this off-chain data such as VCC monitoring data plays a crucial role in the overall system integrity and functionality. Consequently, as this data needs to be introduced by oracles, the issue of trust cannot be entirely resolved by blockchain in the context of verifying VCC data and ensuring its accuracy.

Furthermore, although blockchain's disintermediation and instant settlement can enable efficient market infrastructure, and its openness and technological capabilities, such as token fractionalisation, can promote broader market participation, blockchain usage does not directly guarantee achieving market efficiency. Market efficiency is pri-

marily driven by liquidity, which depends on market activity and interest – factors that blockchain technology alone cannot directly address.

Besides the challenges of VCCs that blockchain cannot fully address, the use of blockchain for VCC tokenisation also introduces new challenges. If tokenisation is not implemented natively and the VCC registry is merely mapped onto the blockchain without full integration, a new potential point of failure is created. Ensuring that ownership and control of the token correspond to ownership and control of the VCC is essential to prevent the same VCC from being tokenised multiple times or transferred or retired independently of the token.⁵⁰ Additionally, managing data transparency, identifiability, and privacy on blockchains can present risks. While blockchain's openness and transparency can address some data privacy issues, pseudonymity can lead to inferences about actors and their identities, which is insufficient for regulatory compliance.⁵¹ Actors requiring regulatory adherence, such as financial institutions, need additional measures to identify other actors to comply with regulations like KYC, AML, and CFT.

To date, mass adoption of tokenised VCCs, or VCCs in general, remains limited, and the overall market has significantly declined despite sustainability continuing to be a top priority for politics, society, and the economy.⁵² This missing adoption is also reflected by the scarcity of academic literature on the topic of VCC tokenisation and long-lasting real-world cases, which could serve as an exhaustive case study. Effectively addressing these challenges and combining blockchain's capabilities with other solutions that can tackle the challenges blockchain alone cannot address is crucial for the successful implementation and widespread adoption of VCCs and might even uncover new blockchain use cases in the context of VCCs, not present in the current literature or practice. In this context, research requires interdisciplinary collaboration to investigate how technical, economic, and legal measures can be combined to tackle VCC challenges in an all-encompassing manner. On the technical side, researchers should especially focus on combining blockchain with other technological primitives such as Zero-Knowledge Proofs, for example, for integrating off-chain data into blockchain systems in a secure and verifiable manner.⁵³ Practitioners in the field then need to collaborate closely with technologists to implement and test these integrated solutions in real-world settings. This involves piloting projects that utilise blockchain for VCC management, ensuring that tokenisation processes are secure and accurately reflect VCC ownership and control. Practitioners should also develop best practices for maintaining data transparency, identifiability, and privacy on blockchain platforms while obeying regulatory requirements. Regulatory authorities play a critical role in creating a conducive environment for the adoption of blockchain-integrated VCC systems. They should establish clear guidelines and standards for blockchain use in the VCC market, addressing issues such as compliance with KYC, AML, and CFT regulations. Regulatory bodies might also facilitate collaboration between stakeholders by supporting pilot projects and offering regulatory sandboxes for testing innovative solutions.

By addressing these challenges through a collaborative and interdisciplinary approach, stakeholders can ensure the successful implementation and widespread adoption of VCCs. This collective effort could also lead to the discovery of further blockchain applications and solutions that can more effectively address the complexities of the VCC market, ultimately contributing to global sustainability goals.

Notes

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