From Carbon Records to Climate Finance Infrastructure: Social, Institutional, and Governance Implications of Blockchain-Based Carbon Acidization

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Abstract

Blockchain-based carbon association is increasingly discussed as a means of converting verified emission records into tradable, collateralizable, and auditable climate finance instruments. Yet the technical emphasis on distributed ledgers, smart contracts, and tokenized credits often understates the social and institutional conditions that determine whether such systems improve climate governance or merely reproduce existing market weaknesses in digital form. This article develops a governance-centered review and analytical framework for blockchain-enabled carbon association. Drawing on the research direction of trustworthy carbon data accounting, verification, and asset circulation, the article examines how carbon records move from measurement, reporting, and verification systems into registries, tokens, markets, and financial disclosure pipelines. The review identifies four linked evaluation dimensions: environmental integrity, institutional accountability, market stability, and social legitimacy. A comparative scenario analysis shows that blockchain infrastructure may reduce verification latency and double-counting risk, but it also introduces new governance risks related to privacy, speculative liquidity, protocol dependence, and uneven access for smaller firms and communities. The article contributes a socio-technical framework that connects carbon data reliability with climate finance infrastructure design. The findings suggest that blockchain-based carbon associations should be governed as public-interest financial infrastructure rather than as a purely technological upgrade to carbon markets.

Keywords: blockchain; carbon association; climate finance; carbon accounting; governance; carbon markets; institutional trust

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1. Introduction

Carbon markets depend on the credibility of carbon records. (Kou et al.,2025) A credit, allowance, or token is not valuable because a database assigns it a number; it becomes financially meaningful only when institutions accept that the underlying emission reduction, removal, or avoidance has been measured, reported, verified, and protected against double counting. (Ben-Sasson et al.,2014) The uploaded manuscript on blockchain-supported carbon accounting and asset circulation highlights this central problem by connecting emission monitoring, verification confidence, smart contract execution, and tokenized circulation into a single transformation finance architecture. Building on that research direction, the present article shifts the center of analysis from technical feasibility to the social, institutional, and governance implications of turning carbon records into climate finance infrastructure.

Climate finance has expanded beyond grant funding and public climate commitments. (Howson,2019) Sustainability-linked loans, transition bonds, carbon funds, voluntary carbon markets, compliance markets, and disclosure frameworks increasingly depend on quantified environmental performance. This-Huumo et al.,2016) In this setting, carbon records operate as boundary objects: they are environmental measurements for engineers, compliance evidence for regulators, tradable claims for markets, and reputational signals for firms. The promise of blockchain-based carbon association is that distributed ledgers may preserve provenance, automate validation, reduce settlement frictions, and create a transparent asset trail. These claims are consistent with broader research on blockchain trust, distributed consensus, and industrial information integration.

However, the conversion of carbon data into assets is not merely a data engineering exercise. (Lu,2022) Acidization means that a measured environmental claim is made legible to finance. (Tschorsch et al.,2016) Once emission reductions are tokenized or registered as marketable instruments, the system must answer not only whether data are immutable, but also whose data are represented, who has authority to verify them, who benefits from liquidity, who bears liability if claims fail, and how market incentives affect decarbonization behavior. Earlier financialization research shows that the transformation of nonfinancial phenomena into tradable assets can change institutional priorities and redistribute risks. Carbon association therefore requires a governance lens that integrates data reliability with accountability, legitimacy, and distributive consequences.

The article addresses three questions. (Schneider et al.,2019) First, how does blockchain-based carbon association reorganize the relationship between carbon accounting and climate finance? (Li et al.,2019) Second, what social and institutional risks arise when verified carbon records become tokenized financial objects? Third, what governance principles should guide the design of carbon asset infrastructure so that it strengthens climate accountability rather than creating a faster but less legitimate market? The contribution is a review-based conceptual framework supported by scenario analysis. The article does not argue that blockchain is a universal solution. Instead, it treats blockchain as a configurable institutional technology whose climate value depends on verification rules, legal recognition, market design, and public accountability.

Figure 1 presents the conceptual pathway used in this article. Carbon records originate in monitoring and reporting systems; verification institutions assess quality, additionality, and baseline alignment; blockchain registries store identifiers and transaction histories; and climate finance actors use these records in trading, collateral, sustainability-linked instruments, or retirement claims. The pathway clarifies that the governance problem is not limited to the ledger. Each stage contains opportunities for transparency and points of failure.

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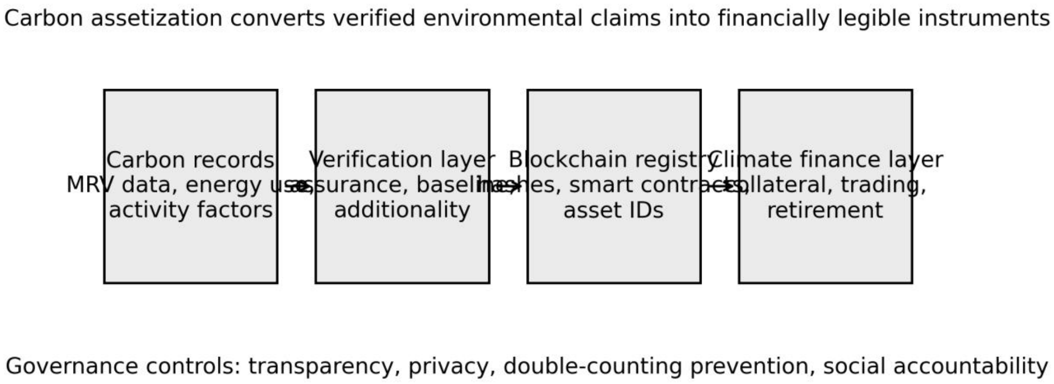

Figure 1. Carbon record-to-climate finance infrastructure pathway for blockchain-based association.

2. Literature Background and Research Context

Research on carbon accounting has long emphasized the role of standardized measurement, reporting, and verification in producing comparable emission records. (Xu et al.,2024) Corporate inventories, life-cycle assessments, project-based offset standards, and national greenhouse gas accounting systems each serve different policy needs. (Mendling et al.,2018) While these systems vary in scope and rigor, they share a common dependence on data quality, organizational capacity, baseline assumptions, and auditability. Carbon association increases the stakes of accounting because records become linked to financial claims. If the underlying record is incomplete or weakly verified, financial instruments built on that record may amplify rather than resolve trust problems.

Blockchain scholarship has explored distributed ledgers as infrastructures for trust, traceability, and automation. (MacKenzie,2009) In industrial and supply chain settings, blockchain has been proposed to improve provenance tracking, reduce tampering, and enable cross-organizational coordination without a single dominant intermediary. (Angelis et al.,2018) In information systems research, blockchain is also understood as a governance mechanism that combines technical rules with institutional participation, incentive design, and boundary-setting. These insights are directly relevant to carbon markets, where no single database can resolve disputes over additionality, permanence, leakage, or social harm if those questions are not embedded in the system design.

Carbon market studies provide a second foundation. (Zhang et al.,2025) Compliance markets such as the European Union Emissions Trading System demonstrate that carbon assets may create price signals for emission reductions, but they also reveal persistent governance problems, including over-allocation, price volatility, political bargaining, and uneven sectoral coverage. (Reijers et al.,2016) Voluntary carbon markets add further complexity because project quality, crediting methods, and buyer claims differ across standards. Research on offset markets has criticized weak additionality, uncertain permanence, and the tendency for commodified credits to obscure local social and ecological effects.

Financial technology research adds another dimension. (Hepburn,2007) Tokenization can improve divisibility, programmability, and settlement efficiency, but it can also detach asset circulation from underlying real-world performance. (Ostrom,1990) Stablecoins, decentralized finance, and security tokens illustrate how digital liquidity can accelerate financial activity before legal and prudential safeguards mature. Carbon tokens may therefore produce a paradox: the same features that make assets liquid and programmable can increase speculation, greenwashing, and systemic dependence on private platforms. This paradox should be addressed before blockchain carbon assets are scaled into climate finance systems.

The uploaded carbon accounting manuscript uses blockchain to integrate emission monitoring, verification, tokenization, and asset circulation, with emphasis on reliability indexes, verification delays, and transaction transparency. (Chen et al.,2024) The present article extends this line of work by asking how such infrastructure should be governed once it becomes socially consequential. (North,1990) A ledger can preserve records, but it cannot independently determine whether a baseline is fair, whether a community was consulted, whether a transition pathway is credible, or whether financial value encourages actual decarbonization. Those judgments require institutional design.

An important gap in this literature concerns information asymmetry between record producers and asset users. Industrial operators, project developers, verifiers, exchangers, investors, and final buyers do not observe the same information. Operators may know whether emission reductions were created by structural change or temporary operational adjustment, while investors may only see a certificate, a registry entry, or a token identifier. Blockchain can reduce some asymmetry by preserving provenance and transaction histories, but it can also create a false sense of certainty when users confuse a transparent transaction record with verified environmental performance. A governance-centered review must therefore examine both the information that the ledger reveals and the information that remains outside the ledger, including baseline assumptions, audit quality, social safeguards, and the economic incentives of intermediaries. This distinction is central because climate finance instruments are only as credible as the measurement and verification arrangements that support them. (MacKenzie,2009; Gillenwater,2012)

3. Conceptual Framework: From Records to Assets

The framework developed here treats blockchain-based carbon assetization as a four-stage socio-technical process. (Klenert et al.,2018) The first stage is recording production (Stern,2007). Carbon records may be generated from direct emissions monitoring, energy consumption data, industrial activity data, remote sensing, or modeled estimates. Their quality depends on sensor calibration, boundary definitions, data completeness, and the method used to convert activity into carbon-equivalent estimates. The second stage is verification. Independent verifiers or automated rules assess whether records correspond to eligible reductions, removals, or avoided emissions. The third stage is association. Verified claims are assigned unique identifiers, recorded in registries, and represented as credits, tokens, certificates, or collateralizable instruments. The fourth stage is financial circulation. Assets are traded, retired, used for claims, or linked to financing contracts.

These stages are not neutral processes. (Lu et al.,2024) Each one shapes the meaning of the carbon asset. (Bebbington et al.,2008) If record production privileges large firms with sophisticated monitoring systems, smaller suppliers may be excluded from climate finance. If verification relies on opaque algorithms, accountability may weaken even when transaction logs are transparent. If tokenization makes credits highly divisible and tradable, market liquidity may increase while the connection to local climate benefit becomes less visible. If financial circulation rewards short-term trading volume, the system may prioritize exchangeability over decarbonization. The governance of association must therefore examine not only technical integrity but also institutional incentives.

Environmental integrity is the first evaluation dimension. (Cong et al.,2019) A carbon asset should correspond to a real, additional, measurable, durable, and non-duplicated environmental outcome. (Ascui et al.,2011) Blockchain can strengthen uniqueness and transaction traceability, but it cannot by itself guarantee additionality or permanence. Institutional accountability is the second dimension. Actors who measure, verify, issue, transfer, and retire carbon assets must be identifiable, auditable, and subject to correction. Market stability is the third dimension. Tokenized assets require safeguards against manipulation, excessive speculation, liquidity shocks, and unreliable bridges between registries. Social legitimacy is the fourth dimension. Communities affected by carbon projects, industrial transitions, or offset claims should be visible in governance processes rather than reduced to metadata.

The framework also distinguishes between data transparency and governance transparency. (Yang et al.,2025) Data transparency means that records, hashes, timestamps, and ownership histories can be inspected. (Lohmann,2009) Governance transparency means that rules for eligibility, appeals, verification, conflict of interest management, and public oversight can be understood and challenged. A blockchain platform may provide the first while lacking the second. For climate finance, the second is essential because carbon assets carry public consequences beyond private transactions.

4. Social Implications of Carbon Acidization

The social implications of blockchain-based carbon association begin with inclusion. (Calel et al.,2016) Many carbon accounting systems favor actors with technical capacity, professional consultants, and established reporting routines. (Ratnatunga et al.,2011) If tokenized carbon finance rewards high-resolution data without addressing capacity gaps, it may concentrate benefits among large industrial firms, project developers, and digital intermediaries. Small enterprises and community projects may face higher relative costs for monitoring, verification, and platform participation. This would reproduce an old problem in a new technical format: the entities most able to document reductions receive financial recognition, while those with limited administrative capacity remain outside the market.

A second social implication concerns the visibility of local effects. (Wu et al.,2025) Carbon assets often abstract complex socio-ecological relations into standardized units. (Stechemesser et al.,2012) This abstraction is useful for markets, but it may hide distributional consequences. For example, a project that generates credit through land management, renewable infrastructure, or industrial transition may affect employment, land access, local pollution, and community decision-making. If these effects are not encoded in governance procedures, a token may circulate as a clean climate asset even when the project context is contested. Studies of carbon offsetting show that social legitimacy cannot be inferred from carbon quantity alone.

Privacy is another issue. (Kshetri,2018) Carbon records can reveal production volumes, energy intensity, supply relationships, equipment performance, and operational schedules. (Tang et al.,2019) A fully transparent ledger may create commercial or security risks if sensitive industrial information is exposed. Conversely, excessive privacy protections may prevent public scrutiny and weaken confidence. The governance challenge is to design layered transparency: public identifiers for assets and retirement claims, auditable evidence trails for regulators and accredited verifiers, and privacy-preserving methods for commercially sensitive operational data. Zero-knowledge proofs and selective disclosure may support this balance, but they require institutional oversight to remain credible.

Labor and procedural justice deserve particular attention because carbon association may reshape incentives inside carbon-intensive sectors. If firms receive finance for verified reductions, managers may prioritize activities that produce measurable creditable outcomes while overlooking less visible worker safety, retraining, or community transition needs. A steel plant, logistics operator, or energy facility may reduce reported emissions through fuel switching or process optimization, but the social value of that transition depends on who bears the cost, who receives the financial benefit, and whether affected workers have a voice in implementation. Tokenized assets should therefore include governance fields that record safeguard review, stakeholder consultation, grievance procedures, and benefit-sharing arrangements. These fields should not become empty compliance labels. They should be linked to auditable documents, review dates, and responsible institutions so that social claims can be checked alongside carbon claims. (Klenert et al.,2018; Bebbington et al.,2008)

Carbon association also changes the social meaning of climate responsibility. (Lu,2019) When firms purchase tokens or retire credits, responsibility may shift from direct operational change toward financial compensation. (Bocken et al.,2014) This is not necessarily harmful if offsets are high quality and used only for residual emissions. Yet tokenized markets can make offsetting frictionless, which may encourage substitution of credit purchases for deeper transition. Governance should therefore connect asset use to credible transition planning, disclosure, and limits on claims. Climate finance infrastructure should reward actual decarbonization pathways rather than provide convenient digital instruments for reputational management.

5. Institutional Implications: Authority, Verification, and Liability

Institutions determine whether carbon association is trusted. (Friedlingstein et al.,2022) In centralized registries, authority is concentrated on standard setters, regulators, and auditors. (Geels,2002) In blockchain systems, authority is redistributed across platform operators, smart contract developers, validators, data providers, verifiers, and market participants. This redistribution may reduce single-point control but can also make responsibility harder to assign. If an erroneous credit is issued by a smart contract because input data were flawed, liability may involve the data provider, verifier, oracle operator, protocol designer, and asset buyer. Legal and institutional design must clarify these responsibilities before large-scale adoption.

Verification is especially important. (Xu et al.,2021) Automated smart contracts can enforce rule-based thresholds, document submission, registry uniqueness, and retirement functions. (Markard et al.,2012) They cannot independently interpret ambiguous evidence, assess social safeguards, or resolve disputes over additionality. Hybrid verification is therefore more realistic than full automation. Human and institutional judgment should remain part of eligibility assessment, while blockchain can improve documentation, timestamping, workflow transparency, and audit trails. This hybrid design is consistent with studies of algorithmic governance that caution against replacing institutional accountability with automation.

Liability allocation is a further institutional requirement. When an asset is later found to be over-credited, duplicated, or socially harmful, the system needs a clear mechanism for correction and responsibility. Possible remedies include credit suspension, forced retirement, replacement obligations, financial penalties, verifier review, and public disclosure of the error. A purely technical registry cannot determine which remedy is legitimate because liability depends on contractual relationships, standard-setting rules, securities law, environmental regulation, and consumer protection norms. The governance architecture should therefore specify who may challenge an asset, who investigates the challenge, how long evidence is retained, what happens to downstream holders, and whether good-faith buyers are protected. Without these rules, a highly liquid carbon asset may transmit errors across portfolios faster than institutions can correct them. (North,1990; Treiblmaier,2018)

Oracles form another institutional weak point. (Treiblmaier,2018) Blockchain systems depend on off-chain data to represent real-world events. (Rennings,2000) Carbon records originate outside the ledger, so the reliability of the asset depends on the integrity of sensors, reports, satellite data, audit documents, and verification decisions. This is the oracle problem in climate form. A distributed ledger can make a false record immutable, but

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immutability does not make the record true. Governance must therefore define approved data sources, uncertainty thresholds, audit sampling, recalibration rules, and procedures for correcting or quarantining disputed records.

Institutional interoperability is also necessary. (Lu,2017) Carbon assets may interact with voluntary standards, national registries, compliance markets, corporate disclosure systems, and financial regulators. (Porter et al.,1995) If tokenized assets are not recognized by these institutions, they may remain speculative instruments with limited climate value. If they are recognized too quickly without safeguards, weak assets may enter regulated finance. Interoperability should therefore be gradual, conditional, and based on shared metadata standards, identity rules, retirement protocols, and public accountability mechanisms.

6. Governance Risks and Comparative Scenario Analysis

To translate the conceptual discussion into an analytical comparison, this article develops a scenario-based governance matrix. (Saberi et al.,2019) The matrix compares four institutional configurations: a centralized registry, hybrid digital reporting, a permission blockchain registry, and an open token market. (Stavins,2008) The scores are interpretive rather than empirical measurements; they synthesize risk exposure across six domains: data quality, additionality, double counting, speculation, equity impact, and privacy. The purpose is to show how blockchain can reduce some risks while increasing others if governance safeguards are weak.

The scenario analysis uses qualitative scoring logic rather than a statistical model. Each infrastructure type is assessed according to its expected exposure to record manipulation, verification delay, double counting, speculative circulation, privacy leakage, and exclusion of smaller actors. Scores are intended to support comparative reasoning, not to produce definitive rankings. The value of the analysis lies in showing that different governance objectives can move in opposite directions. For example, open token markets may score well on liquidity and settlement speed while scoring poorly on speculative risk and institutional accountability. Centralized registries may perform better on legal authority but worse on transparency and cross-border interoperability. The most robust configuration is therefore not the most decentralized or the most centralized model; it is the model that aligns technical design with enforceable governance functions. (Stavins,2008; Zetzsche et al.,2020)

The matrix in Figure 2 indicates that permissioned blockchain registries have lower double-counting exposure than conventional systems because each asset can be assigned a unique identifier, ownership trail, and retirement status. (Zheng et al.,2022) However, open token markets show higher speculation and equity risks because liquidity may attract financial actors whose incentives differ from those of decarbonization policy. (Aldy et al.,2010) This finding is consistent with financial innovation research showing that market efficiency and social value do not automatically move together. Governance must therefore distinguish between liquidity that helps climate finance reach projects and liquidity that detaches asset prices from environmental performance.

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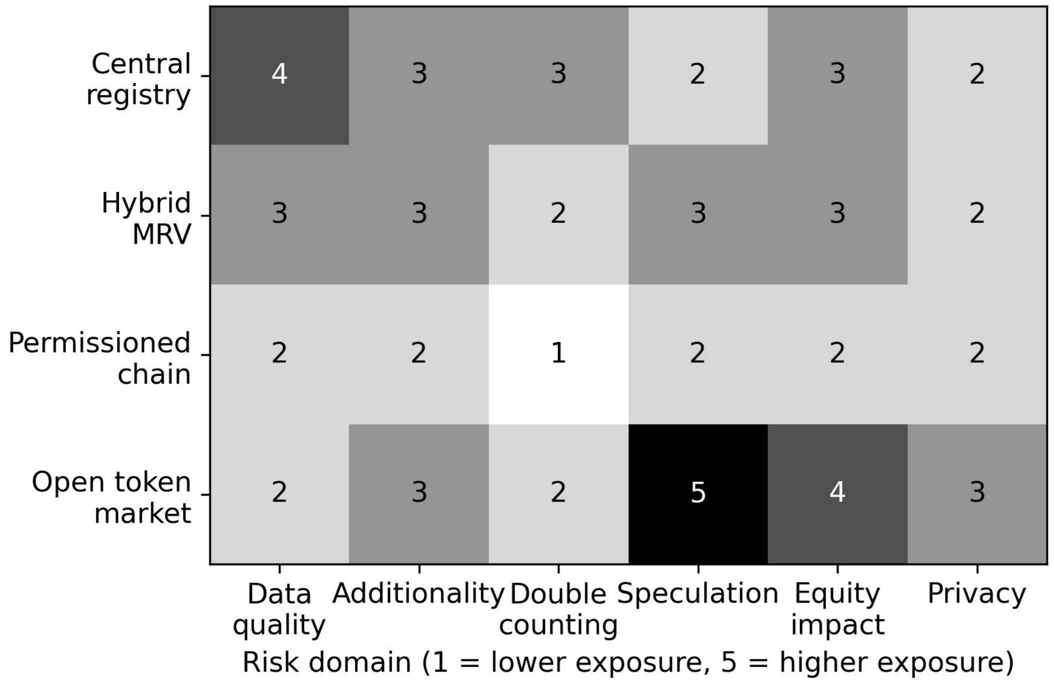

Figure 2. Governance risk matrix across carbon asset infrastructure configurations.

The analysis also considers verification latency. (Zetzsche et al.,2020) Figure 3 presents a stylized scenario in which manual registry systems reduce verification delays slowly, while blockchain-supported workflows reduce delays more rapidly through standardized data submission, smart-contract workflow checks, and shared audit trails. (Flachsland et al.,2009) The strongest improvement appears in the scenario that combines blockchain with social safeguards because disputes and missing documentation are addressed earlier in the project lifecycle. The implication is that good governance may improve efficiency rather than slow it down. Clear rules, transparent appeals, and quality metadata reduce rework and uncertainty.

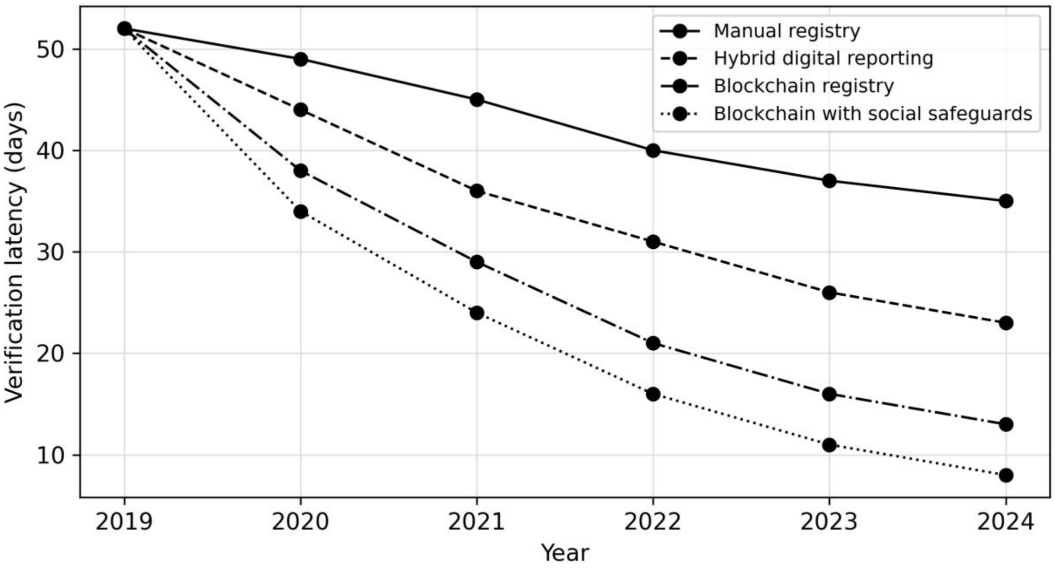

Figure 3. Scenario comparison of verification latency under alternative carbon asset governance models.

Table 1 summarizes the comparative governance profile. The table shows that blockchain systems have clear advantages in provenance and retirement tracking. Their weaknesses arise in areas that require social judgment, legal enforcement, and macro-financial oversight. This finding supports a central argument of the article: blockchain is valuable as part of climate finance infrastructure only when embedded in institutional arrangements that define authority, rights, responsibilities, and corrective procedures.

Table 1. Comparative governance profile of carbon asset infrastructure models

Governance feature	Central registry	Hybrid digital reporting	Permissioned blockchain	Open token market
Record provenance	Moderate	Moderate to high	High	High but platform-dependent
Double-counting control	Medium	Medium	High	Variable across bridges
Verification accountability	Clear but slow	Shared	Shared and auditable	Fragmented
Market liquidity	Low to medium	Medium	Medium	High
Privacy protection	High internal control	Configurable	Configurable with permissions	Often weak without safeguards
Social inclusion	Limited	Moderate	Moderate to high	Uneven
Regulatory interoperability	High domestically	Medium	High if standardized	Uncertain across platforms

The matrix highlights why the governance of carbon association cannot be assessed through technical transparency alone. (Lu,2018) A permissioned blockchain registry can perform well on double-counting control while still requiring independent oversight for additionality and social effects. (Bodansky,2016) An open token market can produce fast circulation, yet its higher speculation score indicates that liquidity may become a governance risk when market design is separated from climate purpose.

Table 2 indicates that no model is universally superior. (Hertwich et al.,2018) Central registries have clearer legal authority but weaker transparency and slower verification. (Gillenwater,2012) Open token markets have stronger liquidity but weaker institutional control. A permission blockchain model offers a plausible middle path when it is linked to accredited verification, transparent retirement, and public oversight.

7. Design Principles for Governance-Ready Carbon Asset Infrastructure

A governance-ready carbon asset system should begin with data minimalism and data sufficiency. (Lu et al.,2024b) The system should store enough information to verify asset origin, eligibility, ownership, and retirement, but it should not expose unnecessary operational details. (Pattberg et al.,2012) Hashing, permissioned access, and selective disclosure may allow confidential data to be audited without becoming fully public. This approach respects both public-interest transparency and legitimate commercial privacy. It also reduces cybersecurity exposure because sensitive production data are not replicated across unnecessary nodes.

The second principle is separation between verification and market-making. (Catalini et al.,2020) The institutions responsible for verifying emission reductions should not have direct incentives to maximize token issuance or trading volume. (Bulkeley et al.,2014) Conflicts of interest have historically weakened some environmental markets. Blockchain does not remove this concern; it may intensify it if protocol operators, exchanges, and verifiers are financially linked. Governance should require independent verification, transparent fee structures, rotation of auditors, and public reporting of disputes and reversals.

The third principle is asset lifecycle completeness. (Lu et al.,2023) Every carbon asset should have visible status categories: pending, verified, issued, transferred, pledged, retired, suspended, or revoked. (Zhang et al.,2017) Climate claims should only be made against retired assets, and retirement should be irreversible. If assets are bridged across ledgers or platforms, the original registry should lock or mark the asset to prevent duplication. This lifecycle design is more important than the choice of chain architecture because double counting is fundamentally a governance and interoperability problem.

The fourth principle is transition alignment. (Lovell et al.,2010) Carbon assets used in corporate or financial claims should be linked to transition plans, sectoral pathways, or residual emission strategies. (Ellerman et al.,2010) Without this linkage, tokenized credits may function as low friction substitutes for operational decarbonization. Financial institutions should disclose whether carbon assets support mitigation projects, offset residual emissions, collateralize green lending, or satisfy regulatory obligations. Different uses require different levels of scrutiny.

A sixth design principle is modular interoperability. Carbon asset infrastructure should be built so that data capture, verification, issuance, trading, retirement, and claims reporting can be connected without forcing every institution to use one closed platform. Open metadata standards, application programming interfaces, registry bridges, and common retirement identifiers can support interoperability while preserving institutional diversity. At the same time, interoperability should be controlled through accreditation and audit rules. A bridge that moves assets across ledgers without locking or retiring the source record can reproduce the double-counting problem that blockchain is supposed to reduce. Governance-ready interoperability therefore requires both technical connectors and institutional controls, including shared definitions of asset status, evidence quality, reversal rules, and claims eligibility. (Peters et al.,2017; Zhang et al.,2025)

The fifth principle is participatory legitimacy. (Zhang et al.,2021) Communities and workers affected by carbon projects or industrial transition should have channels for notification, consultation, grievance, and benefit-sharing. (Doda,2016) Blockchain tools can document process milestones, but meaningful participation requires institutional procedures outside the code. Governance-ready association should include social safeguard metadata, grievance status indicators, and public summaries of local engagement outcomes.

Table 2. Governance design principles for blockchain-based carbon association

Principle	Governance purpose	Recommended implementation
Data minimalism with audit sufficiency	Balance transparency and confidentiality	Public asset identifiers; restricted evidence room
Independent verification	Reduce conflicts of interest	Accredited verifiers; auditor rotation; dispute publication
Complete asset lifecycle	Preventing double counting and misleading claims	Pending, verified, issued, transferred, pledged, retired, and cancelled states
Transition alignment	Link finance to real decarbonization	Disclosure of asset use in transition plans and reduction pathways
Participatory legitimacy	Address social and local consequences	Community consultation records, grievance channels, and benefit-sharing notes
Interoperable metadata	Support cross-registry accountability	Common identifiers for project, vintage, methodology, verifier, and owner

These principles reframe blockchain carbon infrastructure as an institutional design problem. (Michaelowa et al.,2019) They also provide practical evaluation criteria for regulators, exchanges, standards bodies, project developers, and investors who need to distinguish high-integrity climate finance infrastructure from narrow tokenization products. (Fankhauser et al.,2015)

8. Discussion: Blockchain as Climate Finance Infrastructure

The analysis suggests that blockchain-based carbon association should be understood as climate finance infrastructure. (Lu,2025) Infrastructure is not simply a technical backend; it organizes relations among actors, defines what counts as valid evidence, and distributes power across markets. When carbon records become tokenized assets, the infrastructure affects who can participate in climate finance, what forms of decarbonization are rewarded, and how claims are trusted. The uploaded manuscript's emphasis on trustworthy carbon data accounting and asset circulation is therefore a necessary starting point, but governance must extend the analysis to institutional responsibility and social consequences.

One important implication is that immutability should not be treated as absolute virtue. (Gorwa,2019) Environmental knowledge changes, audits may uncover errors, and social disputes may alter project legitimacy. A responsible carbon ledger must preserve history while allowing correction, suspension, and revocation. This requires governance layers above the ledger, including dispute resolution, legal authority, and transparent reversal procedures. A system that records every transaction permanently but cannot correct invalid assets may be technically immutable and institutionally fragile.

A second implication is that token liquidity must be evaluated against climate outcomes. (Lu et al.,2020) High liquidity can lower transaction costs and attract capital, but it can also encourage short holding periods, derivative speculation, and price volatility. Climate finance requires patient capital for long-term transition. Tokenization should therefore be designed with guardrails, such as holding periods for certain assets, restrictions on unsupported derivatives, public retirement tracking, and disclosure of beneficial ownership in regulated contexts. These safeguards may reduce speculative volume but increase trust.

A third implication is that blockchain should complement, not replace, public regulation. (Spash,2010) Voluntary systems can innovate quickly, but climate claims affect public policy, consumer trust, and financial stability. Regulators should define minimum requirements for carbon asset metadata, registry interoperability, retirement claims, verifier accreditation, and disclosure. Public institutions may also operate or supervise shared registries for high-integrity assets. Private platforms can provide services, but the legitimacy of carbon asset infrastructure depends on public accountability.

The framework also has practical implications for firms, investors, and project developers. (Ye et al.,2022) Companies considering tokenized carbon assets should conduct due diligence beyond price and platform convenience. They should examine the crediting method, project location, verifier independence, asset status, registry linkage, retirement process, and social safeguards. Investors should ask whether association improves the financing of real mitigation or merely creates a tradable wrapper. Project developers should ensure that blockchain reporting does not become a substitute for community engagement and environmental performance.

Figure 4 summarizes the balance required for responsible adoption. Environmental integrity, financial liquidity, and social legitimacy are not interchangeable. A carbon asset system that maximizes liquidity while weakening integrity is not climate finance infrastructure; it is a speculative market. A system that maximizes environmental rigor while excluding smaller actors may be credible but inequitable. A system that emphasizes social legitimacy without reliable records may struggle to attract capital. Governance must hold these dimensions together.

A further implication concerns the temporal character of climate finance. Carbon assets do not only represent past measurement; they also shape expectations about future investment, corporate transition planning, and regulatory credibility. If tokenized assets are treated as short-term trading instruments, infrastructure design may reward volume, speed, and arbitrage. If they are treated as components of transition finance, design priorities shift toward durability, auditability, claims discipline, and alignment with sectoral decarbonization pathways. This distinction matters because a market can be technically efficient while still being climatically ineffective. The purpose of climate finance infrastructure should therefore be evaluated by whether it helps capital move toward credible mitigation, not simply by whether it increases the number of transactions. (Lu,2025; Hepburn,2007)

Empirical work should also examine user behavior around tokenized carbon assets. Future studies could test whether enhanced provenance information changes purchasing decisions, whether investors overvalue liquidity relative to credit quality, and whether companies make different claims when retirement information is visible on a public ledger. Experimental studies, interviews with verifiers and registry operators, and transaction-level analysis could clarify how different actors interpret blockchain evidence. Such research would move the field beyond architectural proposals toward evidence-based governance design. It would also show whether technical transparency improves trust or simply shifts attention away from deeper institutional questions. (Yeung,2018; Victor et al.,2022)

Public communication is also part of infrastructure governance. Many buyers do not distinguish between avoided emissions, reduced emissions, removals, allowances, renewable certificates, and offset credits. Tokenization may worsen this problem if all instruments appear as similar digital assets in wallets or exchanges. Platforms should therefore display plain-language information about asset type, project category, vintage, issuing standard, verification status, retirement eligibility, permanence risk, and allowed claims. This information should be machine-readable for auditors and human-readable for firms, consumers, and regulators. Clear communication reduces the risk that association becomes a marketing technology rather than a climate governance tool. (Sovacool,2021; Michaelowa et al.,2019)

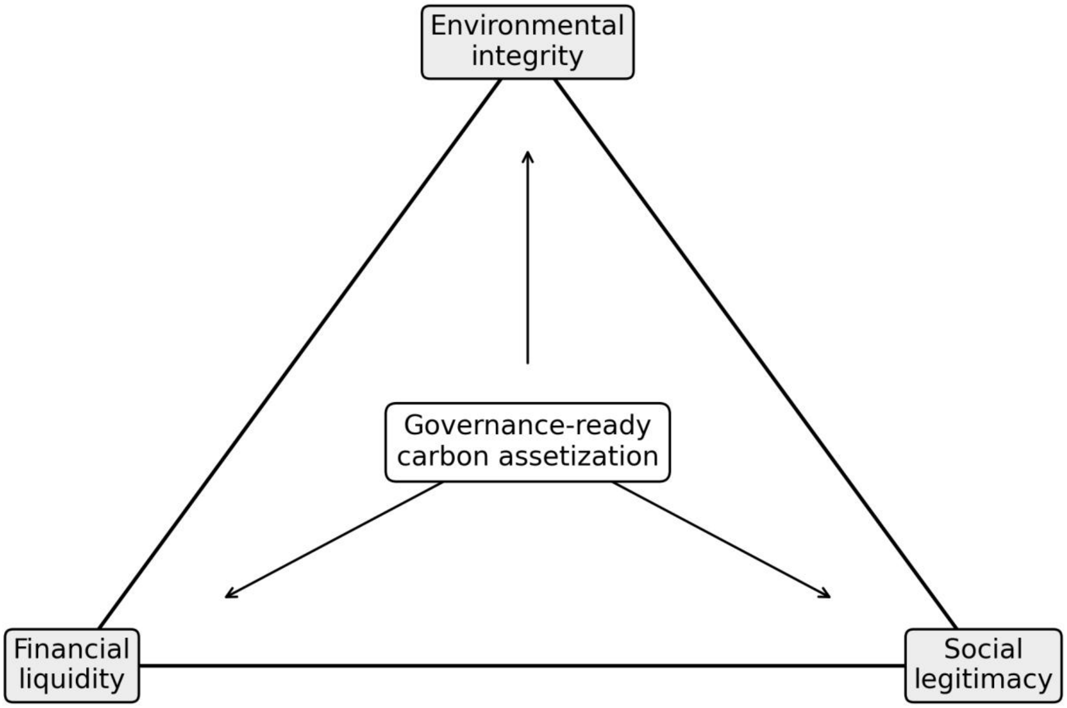

Figure 4. Institutional balance required for governance-ready blockchain carbon assetization.

9. Limitations and Future Research

This article is conceptual and review-based, and its scenario analysis should be interpreted as analytical synthesis rather than a causal test. (de Vries,2018) The scenario analysis is designed to clarify governance trade-offs rather than to estimate causal effects. Future research should test the framework with empirical data from carbon registries, blockchain pilots, voluntary market platforms, and regulated climate finance instruments.

Comparative case studies could examine how different ledger architectures affect verification costs, credit quality, retirement claims, and access for small project developers. Quantitative studies could evaluate whether blockchain registries reduce double-counting incidents or whether risk simply shifts to off-chain data and oracle governance.

Another limitation is that this article treats carbon assets broadly. (Lu et al.,2020b) Different asset types have different governance requirements. Avoided emissions, removals, renewable energy certificates, compliance allowances, biodiversity-linked credits, and industrial transition credits should not be governed identically. Future studies should develop asset-specific governance templates. For example, nature-based removals require permanence and land-right safeguards, while industrial transition assets require baseline control, operational data confidentiality, and sectoral pathway alignment.

Future research should also address legal classification. (Newell et al.,2010) Tokenized carbon assets may be treated as commodities, securities, environmental instruments, contractual claims, or accounting evidence depending on jurisdiction. Legal uncertainty affects investor protection, taxation, disclosure, and enforcement. Interdisciplinary research linking environmental law, financial regulation, information systems, and technology governance is needed to prevent fragmented oversight. Finally, more work is needed on public-interest blockchain design, including low-energy consensus, privacy-preserving auditability, open metadata standards, and institutional mechanisms for correction and appeal.

10. Conclusion

Blockchain-based carbon association has the potential to strengthen carbon market infrastructure by strengthening provenance, reducing settlement friction, recording asset lifecycle events, and connecting verified emission records with climate finance instruments. (Lu et al.,2020c) Yet these benefits are conditional. Distributed ledgers can make carbon records more traceable, but they cannot alone determine environmental integrity, social legitimacy, legal accountability, or transition alignment. The central governance challenge is to ensure that the conversion of carbon records into financial assets supports real decarbonization rather than accelerating a market for weak or poorly understood claims.

This article developed a socio-technical framework for analyzing that challenge. (Victor et al.,2022) The framework connects record production, verification, association, and financial circulation with four evaluation dimensions: environmental integrity, institutional accountability, market stability, and social legitimacy. The comparative analysis shows that blockchain can reduce double counting and verification delays while creating new risks around privacy, speculation, platform dependence, and unequal access. The practical conclusion is that blockchain-based carbon association should be governed as climate finance infrastructure. It requires standards, auditors, public oversight, correction mechanisms, social safeguards, and transition-linked disclosure. When these conditions are present, blockchain may support trustworthy climate finance. Without them, it risks turning carbon uncertainty into digital liquidity.

Ethics approval and consent to participate

Not applicable. This review and scenario analysis did not involve human participants, clinical data, or personal identifiable information.

Consent for publication

Not applicable.

Availability of data and materials

No external dataset was generated. The scenario scores and figures are illustrative analytical materials created for this review.

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Competing interests

The authors declare no competing interests.

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Author contributions

Amirul Hakim Rahman: Conceptualization, methodology, writing - original draft. (Beck et al.,2018) Nur Aisyah Ismail: Literature review, governance analysis, writing - review and editing. Daniel Lim Wei Jian: Scenario analysis, visualization, validation. Farah Nabila Hassan: Supervision, framework development, writing - review and editing.

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