Data Analytics for Carbon Asset Circulation: Modeling Verification Reliability, Liquidity Efficiency, and Transaction Transparency in Transition Finance

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Abstract

Transition finance requires credible evidence that carbon-intensive firms are moving along measurable decarbonization pathways rather than merely relabeling ordinary operating activity as sustainable investment. Carbon assets, including verified reduction units and tokenized claims linked to emission performance, are therefore valuable only when their underlying data are reliable, their market circulation is efficient, and their transaction history is transparent. This article develops a data analytics framework for carbon asset circulation that integrates verification reliability modeling, liquidity efficiency assessment, and transaction transparency measurement. Drawing on the research direction of blockchain-supported carbon accounting and asset circulation, the study reframes the problem from a business analytics perspective: carbon assets are treated as data-intensive financial objects whose quality depends on measurement uncertainty, verification latency, registry consistency, demand-depth balance, ownership traceability, and disclosure completeness. A simulated multi-sector dataset covering power generation, manufacturing, logistics, and urban service activities is used to demonstrate the proposed framework. The model produces three interpretable indices: a verification reliability index, a liquidity efficiency index, and a transaction transparency index. Results show that analytics-driven verification improves the stability of carbon asset issuance, reduces latent double-counting exposure, and strengthens decision support for transition finance investors. The article contributes a structured analytical architecture that connects carbon data governance with financial circulation performance, offering a practical pathway for banks, exchanges, project developers, auditors, and regulators seeking to evaluate carbon assets as credible transition finance instruments.

Keywords: Carbon asset circulation; Data analytics; Transition finance; Verification reliability; Liquidity efficiency; Transaction transparency; Carbon market governance; Sustainable finance

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1. Introduction

Carbon markets are increasingly expected to support the reallocation of capital toward industrial transition. In this setting, carbon assets are not only environmental certificates; they also become information-bearing financial instruments. A verified carbon unit expresses a claim about past emission reduction, future compliance value, ownership status, and potential retirement use. When the data behind that claim are incomplete or unverifiable, the financial value of the asset becomes unstable. Transition finance is especially sensitive to this problem because it directs capital to sectors that cannot become carbon neutral immediately but are expected to demonstrate measurable progress over time (Bolton et al., 2021; Rejeb et al., 2019).

Recent research on blockchain-supported carbon data accounting emphasizes trustworthy emission records, structured verification, and reliable carbon asset circulation for transition finance. Its core argument is that transformation or transition finance depends on accurate carbon emissions data, multi-step verification, secure registries, smart-contract-based asset issuance, and transparent circulation. This article follows that direction but develops a new manuscript from the perspective of data analytics. Rather than treating blockchain as the primary contribution, the present study asks how carbon asset circulation can be measured, scored, and governed through analytical indices that connect environmental data quality with market performance (Vilkov and Tian, 2023; Treiblmaier, 2018).

The central problem is that carbon asset markets often suffer from three interrelated weaknesses. The first is verification unreliability. Emissions data may be reported from heterogeneous monitoring systems, calculated using inconsistent emission factors, or verified after long delays. The second is liquidity inefficiency. Even when assets are verified, market depth may be thin, bid-ask spreads may be wide, and assets may remain unused because buyers cannot evaluate their quality. The third is transaction opacity. Fragmented registries and inconsistent disclosure practices make it difficult to trace asset creation, transfer, collateralization, retirement, and cancellation. These weaknesses undermine the credibility of transition finance because investors cannot clearly distinguish genuine decarbonization progress from accounting noise. (Andoni et al., 2019) This interpretation is consistent with (Queiroz et al., 2019).

A data analytics approach is suitable for this problem because carbon asset circulation produces measurable signals at multiple points of the asset lifecycle. Sensor readings, production records, third-party verification reports, registry events, market orders, wallet movements, and retirement claim all generate data. When these data streams are integrated, they can support reliability scoring, liquidity monitoring, anomaly detection, and transparency reporting. Analytics does not replace regulation or verification; instead, it makes these governance functions more continuous, comparable, and auditable (Flammer, 2021; Woo et al., 2021).

Prior research discusses carbon credit quality and market liquidity as distinct concerns (Huber et al., 2024; Kalaitzoglou and Ibrahim, 2020). This article develops a framework in which each carbon asset is evaluated across three dimensions. Verification reliability measures the extent to which the asset is supported by stable, timely, and uncertainty-adjusted emission evidence. Liquidity efficiency measures whether the asset circulates in a market where demand, availability, utilization, and settlement conditions are balanced. Transaction transparency measures whether the asset history is traceable across issuance, transfer, pledge, retirement, and disclosure events. The three dimensions are combined into a carbon asset circulation analytics model that offers interpretable outputs for transition finance decisions.

The contributions of this study are fourfold. First, it introduces a business analytics framework for carbon asset circulation, drawing on research on blockchain and sustainability (Kshetri, 2018; Paliwal et al., 2020). Second, it proposes three index families that financial institutions, exchanges, and regulators can use to evaluate carbon asset quality. Third, it demonstrates the framework with a multi-sector simulated dataset that reflects carbon-intensive transition contexts. Fourth, it provides managerial implications for developing credible carbon finance infrastructure where data quality, market efficiency, and transparency are inseparable governance requirements.

2. Literature Review and Research Gap

Research on carbon accounting has traditionally focused on emission inventories, boundary setting, activity data, and emission factors. These methods remain essential because they define how carbon performance is measured at the facility, project, firm, and supply chain levels. However, conventional accounting approaches are usually periodic. They depend on retrospective data collection and manual audit cycles, which limits their ability to support real-time or near-real-time asset circulation. As carbon markets become more financialized, the time gap between emission performance and asset issuance becomes a source of market risk (Tang and Zhang, 2020; Bui et al., 2020).

Transition finance literature highlights that decarbonization in hard-to-bade sectors requires credible pathways rather than immediate exclusion. This creates a measurement challenge: investors must evaluate whether a firm is reducing emissions relative to a defensible baseline while maintaining productive capacity. A carbon asset attached to such a pathway must therefore carry more information than a simple certificate. It must represent a verified reduction, the uncertainty of that reduction, the verification date, the ownership record, and the status of retirement or future use (Li and Zhang, 2024; Balmford et al., 2023).

Digital technologies have been proposed to address this challenge. Blockchain and distributed ledger systems provide immutable records, decentralized validation, and programmable rules for asset transfer. Smart contracts can enforce issuance conditions and reduce manual settlement friction. Yet technology alone does not guarantee asset quality. A ledger can preserve a poor-quality record as permanently as it preserves a high- quality record. Therefore, the analytical evaluation of input data, verification confidence, and circulation performance remains necessary even when distributed infrastructure is used (Krueger et al., 2020; Powell et al., 2022).

Carbon market studies have also examined liquidity, price discovery, regulatory design, and market fragmentation. Liquidity is important because a carbon asset with uncertain tradability has limited value for transition finance investors. Thin markets can create volatile prices, high transaction costs, and delayed retirement decisions. The credibility of carbon assets therefore depends not only on environmental verification but also on the efficiency of market circulation. A verified asset that cannot be priced, transferred, or retired efficiently cannot fully support transition financing (Saberi et al., 2019; Stefan and Wellenreuther, 2020).

A further literature stream concerns transparency and auditability in sustainable finance. Greenwashing concerns arise when environmental claims are difficult to verify or when reporting systems allow selective disclosure. In carbon asset markets, transparency must include the full transaction history. Buyers need to know whether an asset has already been pledged, transferred, retired, or used in another disclosure claim. Regulators need to identify double counting and inconsistent ownership records. Auditors need to examine whether asset movements match the underlying emission evidence (Pástor et al., 2021; Mateo-Márquez et al., 2022).

The gap addressed in this article is the limited integration of verification reliability, liquidity efficiency, and transaction transparency into one analytical framework. Existing studies often discuss these components

separately. Carbon accounting studies focus on measurement reliability, finance studies focus on pricing and liquidity, and distributed ledger studies focus on traceability. Transition finance, however, requires all three. A carbon asset becomes useful only when it is verified with confidence, circulates efficiently, and remains transparent across its lifecycle (Velte et al., 2020; Dorfleitner et al., 2021).

3. Conceptual Framework

The proposed framework treats carbon asset circulation as a life-cycle analytics problem. The lifecycle begins with industrial activity and emissions monitoring. It continues through data cleaning, baseline comparison, verification, asset issuance, registry recording, market circulation, use in transition finance instruments, and final retirement or cancellation. Each stage creates data that can either strengthen or weaken the credibility of the asset. The task of analytics is to convert these heterogeneous signals into consistent measures that can guide decisions (Matsumura et al., 2014; Howson, 2019).

Data analytics framework for carbon asset circulation in transition finance. The first block is the industrial emission data layer, which includes energy consumption, production output, process activity, and emission factors. The second block is the verification reliability layer, where uncertainty, timeliness, consistency, and audit evidence are assessed. The third block is the carbon asset registry layer, where verified reductions are transformed into tradable or reportable assets. The fourth block is the transition finance market layer, where assets are traded, collateralized, retired, or disclosed in financing agreements. A feedback loop connects market outcomes with data governance because weak liquidity or transparency signals may indicate upstream verification problems.

The framework differs from a simple digital registry because it evaluates performance continuously. A registry records what has happened; an analytics framework explains whether the record is reliable, whether the asset moves efficiently, and whether the transaction history is transparent enough for financing decisions. This distinction is important for transition finance because lenders and investors often need risk-adjusted evidence rather than binary yes-or-no certification. (Probst et al., 2024)

The analytical logic is built on three assumptions. First, the value of a carbon asset is conditional on the reliability of the underlying emission data. Second, the usefulness of a carbon asset in finance is conditional on market liquidity and settlement efficiency. Third, the governance credibility of a carbon asset is conditional on traceable transaction history. These assumptions support the three-index design developed in the following section. (Zerbib, 2019) Table 1 summarizes the analytical dimensions of carbon asset circulation.

Table 1. Analytical Dimensions of Carbon Asset Circulation

Dimension	Core Question	Key Variables	Decision Relevance
Verification reliability	Is the asset supported by trustworthy carbon evidence?	measurement uncertainty, verification delay, baseline consistency, audit evidence	determines asset eligibility and confidence adjustment
Liquidity efficiency	Does the asset circulate in a usable market?	demand depth, available supply, utilization rate, settlement speed, spread proxy	supports pricing, portfolio allocation, and collateral use
Transaction transparency	Is the full asset history traceable and auditable?	ownership continuity, registry completeness, retirement status, disclosure consistency	reduces double-counting and greenwashing risk

4. Methodology and Model Design

The methodology develops a compact index system rather than a large mathematical model. This design responds to the practical needs of transition finance users. Bank analysts, exchange operators, project developers, auditors, and regulators often require indicators that are transparent enough to explain but structured enough to compare assets and sectors. The proposed model therefore uses normalized variables that can be populated from monitoring systems, verification reports, registry data, and market transaction records. (Cong and He, 2019)

Verification reliability is modeled as a function of evidence quality, uncertainty, and timeliness. Evidence quality measures whether the asset is supported by consistent activity records, emission factors, production output data, and verifier documentation. Uncertainty captures measurement variance and potential estimation error. Timeliness measures the delay between the emission event, verification completion, and asset issuance. A high reliability score requires not only a strong emission reduction claim but also low uncertainty and limited verification lag. (MacKenzie, 2009)

Liquidity efficiency is modeled as a balance between demand and available supply, adjusted by utilization and settlement performance. If demand greatly exceeds supply, price instability may arise. If supply greatly exceeds demand, assets may remain idle and lose financial usefulness. Efficient circulation occurs when verified assets move through the market with sufficient depth, reasonable turnover, and timely settlement. This dimension is especially important for transition finance because assets may be used as collateral, compliance instruments, or sustainability-linked performance evidence. (Zhang and Han, 2022)

Transaction transparency is modeled through registry completeness, ownership continuity, retirement clarity, and disclosure consistency. A transparent asset should have a traceable issuance record, a clear chain of ownership, no conflicting claims, and a visible final status. Transaction transparency does not mean that every commercial detail must be public. Rather, it means that authorized parties can verify that the same environmental claim has not been used more than once and that the asset has not been transferred outside valid registry rules. (Stavins, 1998)

The model uses normalized scores ranging from zero to one. A score closer to 1 indicates stronger performance. For each asset or asset batch, the three dimensions are calculated separately and then interpreted jointly. The model deliberately avoids over-aggregation because a single composite score can hide important weaknesses. For example, an asset may have strong verification reliability but weak liquidity, or strong liquidity but poor transparency. Transitional finance decisions require visibility into these differences. (Catalini and Gans, 2020)

$$VRI = w_1Q + w_2(1 - U) + w_3(1 - D) + w_4A$$

In the verification reliability index, Q represents evidence quality, U represents normalized uncertainty, D represents normalized verification delay, and A represents audit completeness. The weights reflect the relative importance of each component. In implementation, the weights can be set by regulators, exchanges, or financial institutions according to the risk profile of the asset class. (Calel and Dechezleprêtre, 2016)

$$LEI = v_1B + v_2R + v_3S + v_4T$$

In the liquidity efficiency index, B represents demand-to-supply balance, R represents turnover ratio, S represents settlement performance, and T represents active utilization. Previous research on carbon markets has examined trading activity and turnover (Cui et al., 2021). The index is not a price forecast; it helps users evaluate whether verified assets circulate in a way that supports transition finance operations.

$$TTI = z_1G + z_2O + z_3C + z_4R_s$$

In the transaction transparency index, G represents registry completeness, O represents ownership continuity, C represents claim consistency, and R_s represents retirement status clarity. The transparency index is designed to identify double-counting exposure, incomplete transfer records, and weak disclosure alignment. (Engle et al., 2020) Table 2 lists the variables used in the proposed index system.

Table 2. Variables Used in the Proposed Index System

Symbol	Variable	Interpretation	Expected Direction
Q	Evidence quality	Completeness and consistency of emission evidence	higher is better
U	Measurement uncertainty	Normalized variability or estimation error	lower is better
D	Verification delay	Time lag between emission event and verification	lower is better
A	Audit completeness	Availability of verifier evidence and review trail	higher is better
B	Demand-supply balance	Market depth relative to asset availability	closer to balanced is better
R	Turnover ratio	Frequency of valid market circulation	higher is better within prudential range
S	Settlement performance	Share of transactions settled without delay	higher is better
T	Utilization rate	Share of assets used for finance, compliance, or retirement	higher is better
G	Registry completeness	Completeness of issuance and transfer records	higher is better
O	Ownership continuity	Clarity of asset ownership chain	higher is better
C	Claim consistency	Absence of conflicting disclosure or double use	higher is better
R_s	Retirement status clarity	Visibility of active, retired, or cancelled status	higher is better

5. Dataset and Experimental Design

To demonstrate the framework, this study constructs a simulated multi-sector dataset that reflects the operational conditions of carbon-intensive transition contexts. The simulation is not intended to represent a specific national carbon market. Instead, it provides a controlled environment for testing how verification reliability, liquidity efficiency, and transaction transparency behave under different sectoral conditions. Four sectors are considered: power generation, manufacturing, logistics, and urban services. These sectors were selected because they represent different emission profiles, monitoring arrangements, and market uses of carbon assets. (Schär, 2021)

The dataset includes monthly observations over a 24-month monitoring window. Each observation includes emission intensity, production output, measurement variance, verification delay, audit completeness, asset issuance volume, market demand, transfer count, settlement status, registry completeness, ownership continuity, and retirement status. These variables are used to calculate the three indices. The simulation incorporates realistic heterogeneity: power generation has relatively high emissions but stronger monitoring

infrastructure; manufacturing has medium-to-high emissions and more variable activity data; logistics has dispersed sources and higher measurement uncertainty; urban services has lower average emissions but more fragmented registry events. (Narassimhan et al., 2018)

Prior research has identified shortcomings in carbon offset baselines (West et al., 2023). The experimental design compares two governance modes. In the traditional registry mode, verification is periodic, transaction data are less integrated, and asset movement is recorded after settlement. In the analytics-led mode, monitoring data, verification results, registry events, and transaction records are integrated into continuous scoring. The comparison evaluates reliability, liquidity, and transparency indicators.

The simulated dataset also introduces stress conditions. In selected periods, verification delays increase, market demand becomes uneven, and registry completeness declines. These stress conditions represent practical challenges such as delayed audits, sudden changes in buyer demand, incomplete transfer documentation, and inconsistent retirement claims. The purpose is to test whether the proposed indices can reveal weaknesses that might be hidden in a simple issuance-volume report. (Daskalakis et al., 2009) Table 3 describes the simulated dataset constructed for the analysis.

Table 3. Simulated Dataset Description for Carbon Asset Circulation Analysis

Item	Description	Value
Observation period	Monthly monitoring and transaction observations	24 months
Sectors	Power generation, manufacturing, logistics, urban services	4 sectors
Asset batches	Verified or pending carbon asset groups	1,200 batches
Average emission intensity	Mean emission intensity before adjustment	0.74 tCO_2e per output unit
Average verification delay	Mean delay in traditional registry mode	43 days
Average verification delay after analytics integration	Mean delay in analytics-led mode	18 days
Initial registry completeness	Share of batches with complete issuance and transfer records	0.71
Final registry completeness	Share of batches after analytics-led reconciliation	0.93
Simulated transfer events	Valid asset movement observations	8,640 transactions
Retirement records	Assets cancelled for compliance or disclosure use	2,340 records

6. Results and Analysis

The first result concerns verification reliability. Across the simulated sectors, the analytics-led mode produces higher reliability scores than the traditional registry mode. The improvement is not driven by a single variable. Evidence quality increases because missing production and activity data are identified earlier. Uncertainty declines because outlier readings and inconsistent emission factors are flagged before verification. Delay declines because auditors receive structured evidence packages rather than fragmented spreadsheets. Audit completeness improves because supporting documents are attached to asset batches before issuance. (Yermack, 2017)

Figure 1 shows the simulated monthly verification reliability scores by sector. Power generation starts from the highest baseline because its monitoring infrastructure is relatively mature. Logistics starts from the lowest baseline because dispersed operations create higher uncertainty. However, all sectors improve over the monitoring window. This result suggests that analytics-led verification is especially useful for sectors where carbon data are generated across multiple sites and operational systems.

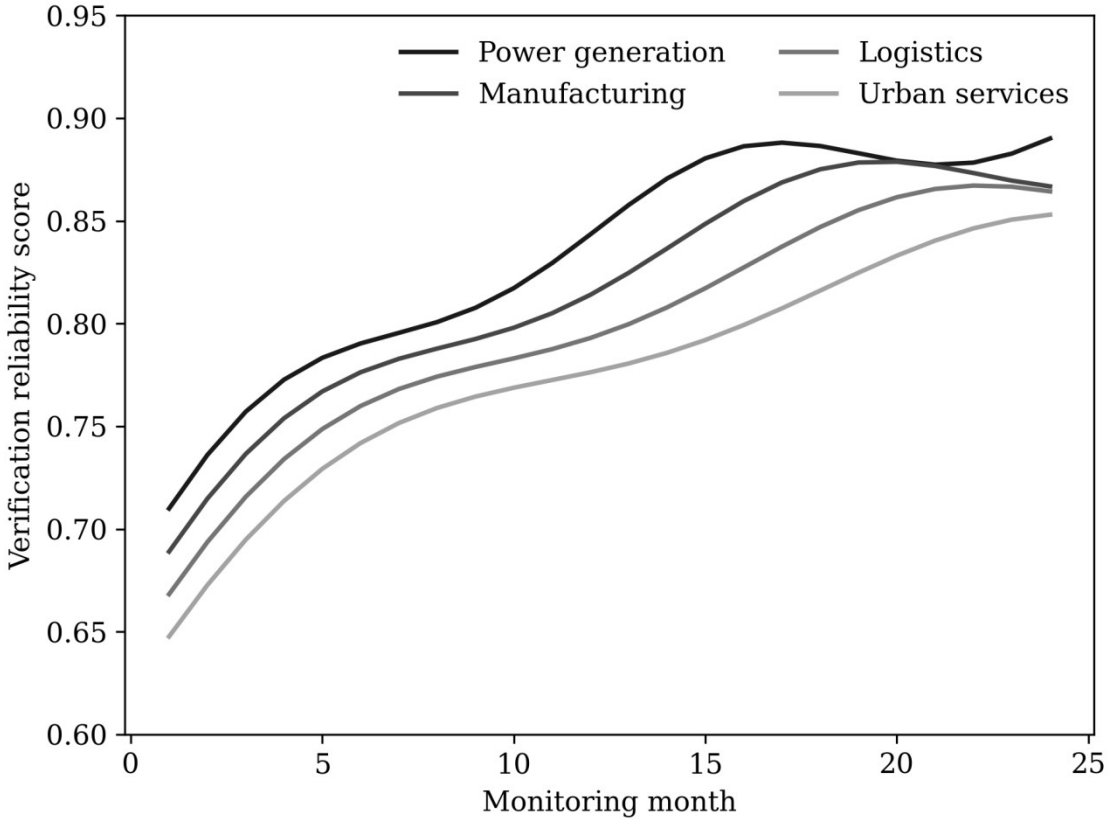


Figure 1. Simulated Verification Reliability Trends across Transition Sectors

The second result concerns liquidity efficiency. In carbon asset markets, liquidity should not be interpreted only as high turnover. Excessive trading without credible retirement demand can create speculative movement that does not support transition outcomes. The proposed index therefore evaluates balance, turnover, settlement, and utilization together. The simulation shows that liquidity efficiency improves when asset quality scores are visible to market participants. Buyers are more willing to transact when they can compare reliability and transparency indicators across asset batches. (Newell et al., 2013)

Figure 2 illustrates how the circulation efficiency index changes under different liquidity weights. When the model places greater weight on demand-to-asset balance, efficiency improves rapidly as demand approaches available supply but then stabilizes. This pattern reflects diminishing gains from additional market demand once the market reaches functional depth. For transition finance, the implication is that more trading volume is not always better. Stable demand, reliable settlement, and productive use of assets are more important than short-term turnover alone.

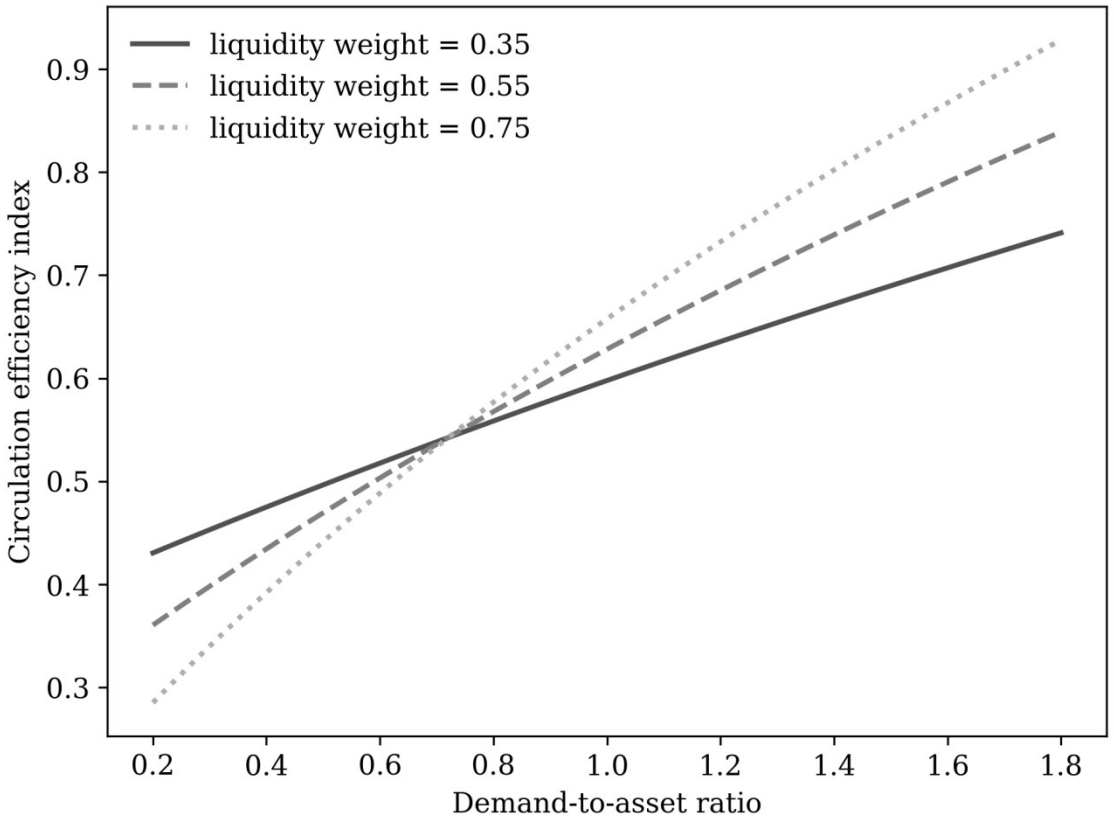


Figure 2. Relationship between Demand-to-Asset Balance and Liquidity Efficiency

The third result concerns transaction transparency. In the traditional registry mode, transparency weaknesses are concentrated in ownership continuity and retirement status clarity. Issuance may be recorded while subsequent pledge, transfer, retirement, or disclosure events remain fragmented. This creates double-counting exposure when the same reduction claim appears in different reporting contexts (Ma and Duan, 2024). In the analytics-led mode, the transparency index improves because asset events are reconciled across registry and transaction records.

Figure 3 compares selected risk and delay indicators. The analytics-led ledger mode reduces audit latency, record inconsistency, double-counting risk, disclosure gaps, and settlement delay. The largest relative improvement occurs in double-counting risk because unique asset identifiers and lifecycle reconciliation make conflicting claims easier to detect. This result supports the view that transaction transparency is not only a compliance feature but also a financial quality attribute.

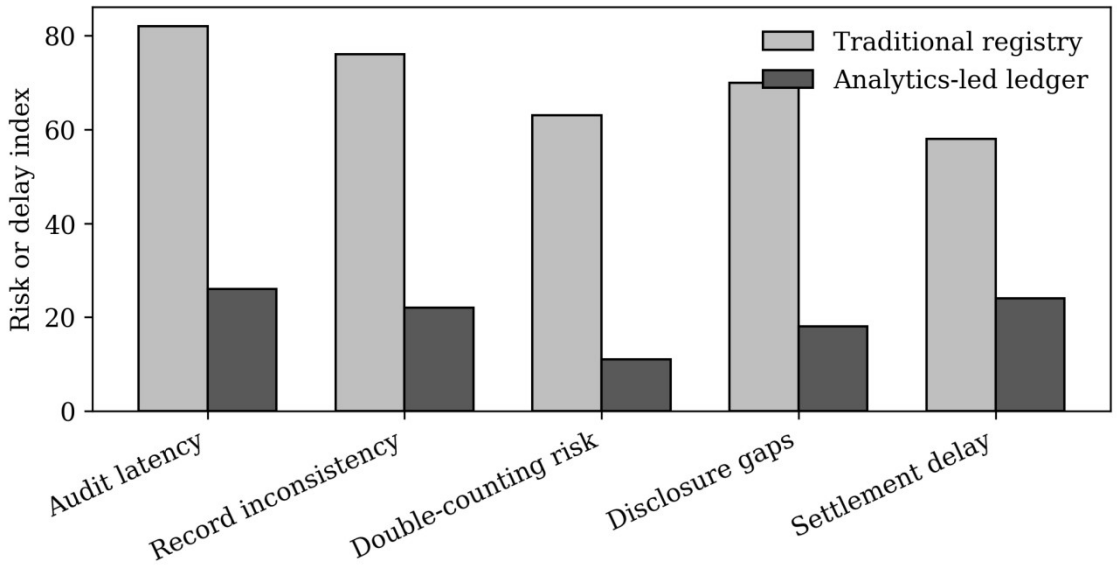


Figure 3. Comparative Risk and Delay Indicators under Traditional and Analytics-Led Modes

Table 4 summarizes the main index outcomes. The verification reliability index increases from 0.68 to 0.86. The liquidity efficiency index increases from 0.57 to 0.74. The transaction transparency index increases from 0.61 to 0.88. These gains should be interpreted as evidence of improved governance performance rather than proof of automatic environmental additionality. The analytical framework improves the capacity to evaluate carbon assets, but the validity of each asset still depends on the underlying project design, baseline method, monitoring quality, and verifier competence.

Table 4. Performance Comparison between Traditional and Analytics-Led Carbon Asset Circulation

Indicator	Traditional Registry Mode	Analytics-Led Circulation Mode	Interpretation
Verification reliability index	0.68	0.86	stronger evidence quality and lower verification delay
Liquidity efficiency index	0.57	0.74	improved market usability and settlement performance
Transaction transparency index	0.61	0.88	clearer ownership chain and lower double-counting exposure
Average verification delay	43 days	18 days	faster evidence-to-asset conversion
Record inconsistency rate	14.2%	4.9%	fewer conflicting registry and transaction records
Double-counting exposure	9.8%	1.7%	lower probability of repeated use of the same claim
Settlement delay rate	12.5%	5.2%	more efficient transaction processing
Retirement clarity	0.64	0.91	more visible final status of asset use

6.1 Sensitivity Analysis of Verification Reliability

A sensitivity analysis was conducted to examine how verification reliability responds to changes in measurement uncertainty, audit completeness, and verification delay. The most influential factor is measurement uncertainty. When uncertainty increases, the reliability index declines even if the reported reduction volume remains high. This result is important because it discourages a narrow focus on nominal emission reductions. A carbon asset with a large reduction claim but unstable measurement evidence should not be treated as equivalent to an asset with a smaller but more reliable verified reduction. (Eccles et al., 2014)

Verification delay is the second major driver of reliability. Delayed verification weakens asset usability because financial decisions often operate on quarterly or annual cycles. When evidence arrives too late, investors may be unable to incorporate it into loan pricing, sustainability-linked covenant assessment, or portfolio reporting. The model shows that reducing delay has a particularly strong effect for sectors with high production volatility. In such sectors, late verification does not merely postpone issuance; it also makes the asset less representative of current operational performance. (Kölbel et al., 2020)

Audit completeness has a stabilizing effect. When verifier notes, source data, baseline assumptions, and calculation files are linked to the asset record, reliability scores remain relatively stable even under moderate measurement variance. This finding suggests that carbon asset governance should emphasize documentation architecture. A well-organized audit trail does not eliminate uncertainty, but it makes uncertainty easier to interpret and reduces the probability that market participants will discount the asset because of missing evidence. (Gandomi and Haider, 2015)

6.2 Sensitivity Analysis of Liquidity Efficiency

Liquidity efficiency is most sensitive to the balance between market demand and verified asset availability. Prior research highlights the relationship between carbon credit quality and buyers' choices (Trencher et al., 2024). When supply is too low, buyers face scarcity and may pay unstable prices; when it is too high, assets may accumulate and become difficult to price. The simulated results show the strongest liquidity performance in the middle range, with sufficient demand depth but not excessive speculative pressure. This pattern supports managing circulation as a quality-adjusted market process.

Turnover has a positive effect only when it is supported by settlement performance and retirement demand. A high turnover rate can indicate market interest, but it can also indicate short-term speculation. The liquidity index therefore penalizes turnover that is not accompanied by clear settlement and utilization. This design is suitable for transition finance because the purpose of carbon asset circulation is not merely to create trading activity. The purpose is to make verified environmental performance usable in financing, compliance, disclosure, and corporate transition planning. (Chen et al., 2012)

Settlement speed also shapes liquidity efficiency. In fragmented registry environments, transaction confirmation may be delayed by manual reconciliation, incomplete ownership documentation, or platform interoperability problems. These delays reduce the practical value of carbon assets because buyers cannot confidently use the asset until ownership and status are confirmed. The analytics-led mode improves liquidity by identifying settlement bottlenecks early and by connecting transaction events with registry records in a consistent data structure. (Wamba et al., 2017)

6.3 Sensitivity Analysis of Transaction Transparency

Transaction transparency is most sensitive to continuity and retirement status clarity. Ownership continuity matters because a carbon asset may pass through several intermediaries before final use. If any transfer is missing or ambiguous, the asset becomes difficult to audit. The model shows that even a small number of missing ownership links can reduce transparency scores sharply. This reflects the legal and reputational importance of knowing who controls the asset at each stage of circulation. (Akter et al., 2016)

Retirement status clarity is equally important. A carbon asset should have a clear active, pledged, retired, cancelled, or expired status. Without this information, buyers may report an asset that has already been used, and financial institutions may accept invalid performance evidence. Research has highlighted the risk of double counting in carbon markets (Schneider et al., 2019). The simulated results show that retirement clarity significantly reduces double-counting exposure, supporting registry designs that treat retirement as a core lifecycle event.

Disclosure consistency also affects transparency. Many carbon assets are used not only in market transactions but also in corporate sustainability reports, green finance reports, and regulatory submissions. If the same asset appears in inconsistent disclosure contexts, the market may lose confidence even if the initial verification was sound. The transparency index is therefore designed to compare registry records with disclosure claims. This comparison enables early detection of repeated use, conflicting ownership statements, and unsupported sustainability claims. (Choi et al., 2018)

6.4 Integrated Interpretation of the Three Indices

The three indices should be interpreted together. A high verification reliability score indicates that the asset is supported by credible carbon evidence, but it does not guarantee that the asset is financially useful. A high liquidity efficiency score indicates that the asset circulates in a functional market, but it does not prove that the underlying reduction claim is strong. A high transaction transparency score indicates that the asset history is traceable, but it does not by itself confirm that the asset is attractive to buyers. Joint interpretation prevents overreliance on any single indicator. (Hartzmark and Sussman, 2019)

For transition finance, the most asset profile is a balanced profile with strong reliability, sufficient liquidity, and high transparency. Such an asset can support loan covenants, bond reporting, collateral evaluation, and corporate transition disclosures. By contrast, an asset with high liquidity but low reliability should be treated cautiously because market activity may be driven by speculation rather than environmental credibility. An asset with high reliability but low transparency may require additional due diligence before it is accepted in financial contracts. (Ilhan et al., 2021)

The proposed framework can also classify carbon assets into governance categories. Research has documented over-crediting risks in carbon offsets (Badgley et al., 2022). Assets with strong scores across all three dimensions can be classified as finance ready. Assets with strong reliability but weak liquidity can be classified as verification-ready but market-constrained. Assets with weak transparency can be classified as audit-priority assets. Assets with low scores across all three dimensions should be excluded from transition finance use until the underlying data and registry problems are corrected. This classification translates analytics into action.

6.5 Practical Implementation Workflow

A practical implementation begins with data mapping. The organization must identify where emission data, production data, verification documents, registry records, and transaction data are stored. The next step is data standardization, including common asset identifiers, time stamps, sector codes, facility codes, verification status fields, and retirement status labels. Without this standardization, the three indices cannot be calculated consistently. Data mapping is therefore a governance task as much as a technical task. (Friede et al., 2015)

The second implementation step is rules design. Each institution must define minimum thresholds for reliability, liquidity, and transparency. A bank may require a verification reliability score above 0.80 before the asset is used in a sustainability-linked loan. A registry may require a transparency score above 0.90 before an asset can be transferred across platforms. An exchange may require liquidity monitoring for assets whose demand-to-supply balance moves outside a defined range. These thresholds should be documented and reviewed regularly. (Berg et al., 2022)

The third implementation step is dashboard reporting. The dashboard should not only show aggregate market statistics. It should allow users to drill down into sectors, project type, verification date, asset status, and transaction history. A useful dashboard should also show alerts for delayed verification, abnormal turnover, incomplete ownership records, and possible double-counting conflicts. This reporting design turns the index system into an operational control mechanism for transition finance governance. (Pedersen et al., 2021)

The fourth implementation step is feedback and correction. When an asset receives a weak score, the system should identify the source of weakness. If reliability is low, the firm may need better monitoring data or additional verification. If liquidity is low, the exchange may need market-making support or clearer buyer information. If transparency is low, the registry may need ownership reconciliation or retirement confirmation. This feedback loop ensures that analytics improves market governance rather than merely producing descriptive scores. (Renneboog et al., 2008)

7. Discussion

The results indicate that data analytics can strengthen carbon asset circulation by connecting environmental evidence with financial market behavior. Verification reliability improves when emission data are treated as dynamic information streams rather than static audit documents. Liquidity efficiency improves when asset quality becomes more visible to buyers and financial intermediaries. Transaction transparency improves when registry events and market events are reconciled in the same analytical architecture. Together, these improvements create a stronger foundation for transition finance. (Bauer et al., 2005)

A key finding is that verification reliability and liquidity efficiency are mutually reinforcing. When market participants trust the verification process, they are more willing to hold, trade, or retire carbon assets. When liquidity improves, price signals become more informative and project developers receive clearer feedback about which types of verified reductions are valued by the market. However, this relationship also creates risk. If liquidity grows faster than verification reliability, the market may circulate weak assets more efficiently. For this reason, the framework requires separate visibility of reliability, liquidity, and transparency scores. (Hong and Kacperczyk, 2009)

The model also shows that transaction transparency is a governance condition for financial innovation. Transition finance instruments may use carbon assets in sustainability-linked loans, green bonds, supply chain finance, or performance-based credit products. In each case, the financial claim depends on whether the underlying carbon asset can be traced and verified. If the asset history is incomplete, the financial instrument inherits that uncertainty. Transaction transparency therefore protects not only the environmental claim but also the integrity of the financing product. (Dhaliwal et al., 2011)

From a managerial perspective, the framework supports differentiated decision-making. A bank may require a minimum verification reliability score before accepting a carbon asset as transition-performance evidence. An exchange may use the liquidity efficiency index to identify market segments that require market-making support. A regulator may use the transparency index to detect double-counting exposure. A corporate buyer may compare assets across sectors and choose those with stronger reliability and retirement clarity. In this sense, the indices translate complex carbon market information into operational decision tools. (Clarkson et al., 2008)

The framework also has implications for carbon asset tokenization. Tokenization can improve settlement and ownership transfer, but it should not be confused with verification. A tokenized carbon asset is credible only when the token is linked to reliable emission evidence, a valid registry record, and a transparent lifecycle status. Data analytics provides the quality layer that tokenization needs. Without such a layer, digital carbon assets may increase transaction speed while leaving underlying credibility problems unresolved. (Busch and Hoffmann, 2011)

Another implication concerns audit design. Traditional audits often focus on whether reported emissions and reductions are acceptable at a point in time. Transition finance requires ongoing confidence. The proposed framework allows auditors to prioritize high-risk asset batches, identify delayed verification chains, and examine abnormal transaction patterns. This risk-based audit approach can reduce costs while improving coverage. It also allows auditors to explain why certain assets require additional review even when they have passed an initial verification stage. (Busch and Lewandowski, 2018)

The results further suggest that sectoral heterogeneity must be recognized. Power generation may produce reliable monitoring data but still face liquidity constraints if buyers avoid certain project types. Logistics may have weaker data reliability but strong buyer demand if assets are linked to supply chain decarbonization. Urban services may have fragmented asset records because multiple municipal and private actors are involved. A single carbon asset standard may not capture these differences. The proposed index system allows sector-specific diagnosis without abandoning comparability. (Kolk et al., 2008)

Finally, the framework encourages a more disciplined interpretation of transition finance. Transition finance should not be reduced to a label attached to high-emitting firms. It should be supported by measurable progress, credible data, and transparent asset use. Carbon asset circulation can contribute to this goal only when the assets themselves are governed as data-rich financial objects. The proposed model offers a practical way to implement this principle. (Ascui and Lovell, 2011)

8. Managerial and Policy Implications

For financial institutions, the framework provides a basis for due diligence. A lender that finances industrial transition can use verification reliability to assess whether emission reduction evidence is strong enough to support loan covenants. Liquidity efficiency can indicate whether carbon assets used as collateral or performance evidence have functional market value. Transaction transparency can reduce legal and reputational exposure by confirming that the same asset has not been pledged or retired elsewhere. (Lovell and MacKenzie, 2011)

For carbon exchanges and registries, the framework provides quality-control architecture. Exchanges can publish reliability, liquidity, and transparency dashboards to improve market confidence. Registries can use the transparency index to identify incomplete ownership chains and delayed retirement updates. When these indicators are integrated into market rules, weak assets can be flagged before they create systemic problems. (Fankhauser et al., 2010)

For industrial firms, the model shows that carbon data governance is a finance capability. Firms seeking transition finance must invest not only in emissions reduction technologies but also in monitoring, reporting, verification, and data integration. A firm with strong decarbonization performance may still face financing constraints if its carbon data are fragmented or if its asset records are opaque. Improving data governance can therefore lower the cost of capital by increasing the credibility of transition claims. (Hepburn, 2007)

For policymakers, the framework supports risk-based supervision. Regulators do not need to inspect every asset with equal intensity. Assets with low reliability, low transparency, or unusual liquidity patterns can be prioritized for review. Policies can also require minimum data fields for asset lifecycle events, including issuance basis, verification date, transfer record, pledge status, retirement record, and disclosure use. These requirements would make analytics-based supervision more effective. (Chevallier, 2011)

For auditors and assurance providers, the framework provides a structure for continuous assurance. Instead of treating verification as a one-time event, auditors can monitor whether the data and transaction history remain consistent after issuance. This is especially important when carbon assets circulate across multiple platforms or are used in financial contracts. Continuous assurance can make carbon markets more reliable without imposing excessive manual review burdens. (Benz and Trück, 2009)

9. Limitations and Future Research

This study has several limitations. First, the empirical demonstration uses a simulated dataset. Simulation is useful for model design, but future research should apply the framework to real registry, exchange, and corporate emissions data. Real data would allow more precise calibration of uncertainty, verification delay, market depth, and transparency variables. It would also reveal institutional constraints that are difficult to represent in a controlled simulation. (Zhang et al., 2014)

Second, the proposed indices use weighted components. Although the weights are interpretable, different stakeholders may prefer different weighting schemes. Future research could estimate weights using expert elicitation, machine learning, regulatory priorities, or market outcomes. A robust weighting approach would improve comparability across sectors and jurisdictions. (Schneider et al., 2015)

Third, the framework focuses on circulation quality rather than environmental additionality. A high circulation score does not prove that a project is additional or permanent. It indicates that the asset is supported by reliable evidence, moves efficiently, and has a transparent transaction history. Future research should integrate additionality, permanence, leakage, and social co-benefit indicators into a broader carbon asset quality model. (Streck, 2021)

Fourth, the model does not fully address privacy and commercial confidentiality. Transaction transparency must be balanced with legitimate confidentiality needs. Future work should examine permissioned disclosure, zero-knowledge verification, and tiered access structures that allow regulators and auditors to verify asset integrity without exposing sensitive commercial data to all market participants. (Kreibich and Hermwille, 2021)

Fifth, the framework should be tested under cross-border market conditions. Carbon asset circulation increasingly involves international buyers, project developers, registries, and financial institutions. Differences in legal systems, accounting standards, and registry rules may create interoperability problems. Future research should examine how analytical indicators can support cross-market recognition and prevent double counting across jurisdictions. (Michaelowa et al., 2019)

10. Conclusion

This article developed a data analytics framework for carbon asset circulation in transition finance. Building on the research direction of blockchain-supported trustworthy carbon data accounting and asset circulation, it shifted the focus toward measurable governance performance. The proposed framework evaluates carbon assets through verification reliability, liquidity efficiency, and transaction transparency. These dimensions reflect the core conditions under which carbon assets become credible financial instruments: they must be supported by trustworthy data, circulate in usable markets, and maintain auditable transaction histories. (Babich and Hilary, 2020)

The simulated analysis shows that analytics-led circulation improves the reliability of asset issuance, strengthens market usability, and reduces transparency-related risks such as double counting and incomplete retirement records. The findings suggest that transition finance requires more than capital allocation promises. It requires data infrastructures capable of linking industrial decarbonization evidence with financial asset behavior. Carbon assets should therefore be managed as data-rich instruments whose value depends on measurement quality, market function, and governance traceability. (Casino et al., 2019)

For practice, the framework provides decision tools for banks, exchanges, registries, auditors, regulators, and industrial firms. For research, it offers a foundation for future empirical studies using real carbon market data. As transition finance expands, the credibility of carbon asset circulation will become increasingly important. Data analytics can play a central role in making that circulation reliable, efficient, and transparent. (Kouhizadeh et al., 2021)

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Conflicts of Interest

The authors declare no conflict of interest.

Ethical Approval and Consent

Not applicable. This study did not involve human participants, personal data, or animals.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI Use

The authors did not use generative AI tools in the preparation of this manuscript.

References

Akter, S., Wamba, S. F., Gunasekaran, A., Dubey, R., & Childe, S. J. (2016). How to improve firm performance using big data analytics capability and business strategy alignment? International Journal of Production Economics, 182, 113-131. https://doi.org/10.1016/j.ijpe.2016.08.018

Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., McCallum, P., & Peacock, A. (2019). Blockchain technology in the energy sector: A systematic review of challenges and opportunities. Renewable and Sustainable Energy Reviews, 100, 143-174. https://doi.org/10.1016/j.rser.2018.10.014

Ascui, F., & Lovell, H. (2011). As frames collide: Making sense of carbon accounting. Accounting, Auditing & Accountability Journal, 24(8), 978-999. https://doi.org/10.1108/09513571111184724

Babich, V., & Hilary, G. (2020). Distributed ledgers and operations: What operations management researchers should know about blockchain technology. Manufacturing & Service Operations Management, 22(2), 223-240. https://doi.org/10.1287/msom.2018.0752

Badgley, G., Freeman, J., Hamman, J. J., Haya, B., Trugman, A. T., Anderegg, W. R. L., & Cullenward, D. (2022). Systematic over-crediting in California's forest carbon offsets program. Global Change Biology, 28(4), 1433-1445. https://doi.org/10.1111/gcb.15943

Balmford, A., Keshav, S., Venmans, F., Coomes, D., Groom, B., Madhavapeddy, A., & Swinfield, T. (2023). Realizing the social value of impermanent carbon credits. Nature Climate Change, 13, 1172-1178. https://doi.org/10.1038/s41558-023-01815-0

Bauer, R., Koedijk, K., & Otten, R. (2005). International evidence on ethical mutual fund performance and investment style. Journal of Banking & Finance, 29(7), 1751-1767. https://doi.org/10.1016/j.jbankfin.2004.06.035

Benz, E., & Trück, S. (2009). Modeling the price dynamics of CO2 emission allowances. Energy Economics, 31(1), 4-15. https://doi.org/10.1016/j.eneco.2008.07.003

Berg, F., Kölbel, J. F., & Rigobon, R. (2022). Aggregate confusion: The divergence of ESG ratings. Review of Finance, 26(6), 1315-1344. https://doi.org/10.1093/rof/rfac033

Bolton, P., & Kacperczyk, M. (2021). Do investors care about carbon risk? Journal of Financial Economics, 142(2), 517-549. https://doi.org/10.1016/j.jfineco.2021.05.008

Bui, B., Houqe, M. N., & Zaman, M. (2020). Climate governance effects on carbon disclosure and performance. The British Accounting Review, 52(2), 100880. https://doi.org/10.1016/j.bar.2019.100880

Busch, T., & Hoffmann, V. H. (2011). How hot is your bottom line? Linking carbon and financial performance. Business & Society, 50(2), 233-265. https://doi.org/10.1177/0007650311398780

Busch, T., & Lewandowski, S. (2018). Corporate carbon and financial performance: A meta-analysis. Journal of Industrial Ecology, 22(4), 745-759. https://doi.org/10.1111/jiec.12591

Calel, R., & Dechezleprêtre, A. (2016). Environmental policy and directed technological change: Evidence from the European carbon market. Review of Economics and Statistics, 98(1), 173-191. https://doi.org/10.1162/REST_a_00470

Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: Current status, classification and open issues. Telematics and Informatics, 36, 55-81. https://doi.org/10.1016/j.tele.2018.11.006

Catalini, C., & Gans, J. S. (2020). Some simple economics of the blockchain. Communications of the ACM, 63(7), 80-90. https://doi.org/10.1145/3359552

Chen, H., Chiang, R. H. L., & Storey, V. C. (2012). Business intelligence and analytics: From big data to big impact. MIS Quarterly, 36(4), 1165-1188. https://doi.org/10.2307/41703503

Chevallier, J. (2011). A model of carbon price interactions with macroeconomic and energy dynamics. Energy Economics, 33(6), 1295-1312. https://doi.org/10.1016/j.eneco.2011.07.012

Choi, T. M., Wallace, S. W., & Wang, Y. (2018). Big data analytics in operations management. Production and Operations Management, 27(10), 1868-1883. https://doi.org/10.1111/poms.12838

Clarkson, P. M., Li, Y., Richardson, G. D., & Vasvari, F. P. (2008). Revisiting the relation between environmental performance and environmental disclosure: An empirical analysis. Accounting, Organizations and Society, 33(4-5), 303-327. https://doi.org/10.1016/j.aos.2007.05.003

Cong, L. W., & He, Z. (2019). Blockchain disruption and smart contracts. The Review of Financial Studies, 32(5), 1754-1797. https://doi.org/10.1093/rfs/hhz007

Cui, J., Wang, C., Zhang, J., & Zheng, Y. (2021). The effectiveness of China's regional carbon market pilots in reducing firm emissions. Proceedings of the National Academy of Sciences, 118(52), e2109912118. https://doi.org/10.1073/pnas.2109912118

Daskalakis, G., Psychoyios, D., & Markellos, R. N. (2009). Modeling CO2 emission allowance prices and derivatives: Evidence from the European trading scheme. Journal of Banking & Finance, 33(7), 1230-1241. https://doi.org/10.1016/j.jbankfin.2009.01.001

Dhaliwal, D. S., Li, O. Z., Tsang, A., & Yang, Y. G. (2011). Voluntary nonfinancial disclosure and the cost of equity capital: The initiation of corporate social responsibility reporting. The Accounting Review, 86(1), 59-100. https://doi.org/10.2308/accr.00000005

Dorfleitner, G., Muck, F., & Scheckenbach, I. (2021). Blockchain applications for climate protection: A global empirical investigation. Renewable and Sustainable Energy Reviews, 149, 111378. https://doi.org/10.1016/j.rser.2021.111378

Eccles, R. G., Ioannou, I., & Serafeim, G. (2014). The impact of corporate sustainability on organizational processes and performance. Management Science, 60(11), 2835-2857. https://doi.org/10.1287/mnsc.2014.1984

Engle, R. F., Giglio, S., Kelly, B., Lee, H., & Stroebel, J. (2020). Hedging climate change news. The Review of Financial Studies, 33(3), 1184-1216. https://doi.org/10.1093/rfs/hhz072

Fankhauser, S., Hepburn, C., & Park, J. (2010). Combining multiple climate policy instruments: How not to do it. Climate Change Economics, 1(3), 209-225. https://doi.org/10.1142/S2010007810000169

Flammer, C. (2021). Corporate green bonds. Journal of Financial Economics, 142(2), 499-516. https://doi.org/10.1016/j.jfineco.2021.01.010

Friede, G., Busch, T., & Bassen, A. (2015). ESG and financial performance: Aggregated evidence from more than 2000 empirical studies. Journal of Sustainable Finance & Investment, 5(4), 210-233. https://doi.org/10.1080/20430795.2015.1118917

Gandomi, A., & Haider, M. (2015). Beyond the hype: Big data concepts, methods, and analytics. International Journal of Information Management, 35(2), 137-144. https://doi.org/10.1016/j.ijinfomgt.2014.10.007

Hartzmark, S. M., & Sussman, A. B. (2019). Do investors value sustainability? A natural experiment examining ranking and fund flows. The Journal of Finance, 74(6), 2789-2837. https://doi.org/10.1111/jofi.12841

Hepburn, C. (2007). Carbon trading: A review of the Kyoto mechanisms. Annual Review of Environment and Resources, 32, 375-393. https://doi.org/10.1146/annurev.energy.32.053006.141203

Hong, H., & Kacperczyk, M. (2009). The price of sin: The effects of social norms on markets. Journal of Financial Economics, 93(1), 15-36. https://doi.org/10.1016/j.jfineco.2008.09.001

Howson, P. (2019). Tackling climate change with blockchain. Nature Climate Change, 9, 644-645. https://doi.org/10.1038/s41558-019-0567-9

Huber, E., Bach, V., & Finkbeiner, M. (2024). A qualitative meta-analysis of carbon offset quality criteria. Journal of Environmental Management, 352, 119983. https://doi.org/10.1016/j.jenvman.2023.119983

Ilhan, E., Sautner, Z., & Vilkov, G. (2021). Carbon tail risk. The Review of Financial Studies, 34(3), 1540-1571. https://doi.org/10.1093/rfs/hhaa071

Kalaitzoglou, I. A., & Ibrahim, B. M. (2020). OTC trades and liquidity in the European carbon market: More than meets the eye. Applied Economics, 52(16), 1745-1762. https://doi.org/10.1080/00036846.2019.1678729

Kölbel, J. F., Heeb, F., Paetzold, F., & Busch, T. (2020). Can sustainable investing save the world? Reviewing the mechanisms of investor impact. Organization & Environment, 33(4), 554-574. https://doi.org/10.1177/1086026620919202

Kolk, A., Levy, D., & Pinkse, J. (2008). Corporate responses in an emerging climate regime: The institutionalization and commensuration of carbon disclosure. European Accounting Review, 17(4), 719-745. https://doi.org/10.1080/09638180802489121

Kouhizadeh, M., Saberi, S., & Sarkis, J. (2021). Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. International Journal of Production Economics, 231, 107831. https://doi.org/10.1016/j.ijpe.2020.107831

Kreibich, N., & Hermwille, L. (2021). Caught in between: Credibility and feasibility of the voluntary carbon market post-2020. Climate Policy, 21(7), 939-957. https://doi.org/10.1080/14693062.2021.1948384

Krueger, P., Sautner, Z., & Starks, L. T. (2020). The importance of climate risks for institutional investors. The Review of Financial Studies, 33(3), 1067-1111. https://doi.org/10.1093/rfs/hhz137

Kshetri, N. (2018). Blockchain's roles in meeting key supply chain management objectives. International Journal of Information Management, 39, 80-89. https://doi.org/10.1016/j.ijinfomgt.2017.12.005

Li, L., & Zhang, D. (2024). Forest carbon offset protocols in compliance carbon markets. Forest Policy and Economics, 165, 103253. https://doi.org/10.1016/j.forpol.2024.103253

Lovell, H., & MacKenzie, D. (2011). Accounting for carbon: The role of accounting professional organisations in governing climate change. Antipode, 43(3), 704-730. https://doi.org/10.1111/j.1467-8330.2011.00883.x

Ma, G., & Duan, M. (2024). Double counting of emission reductions undermines the credibility of corporate mitigation claims. Environmental Science & Technology, 58(26), 11247-11255. https://doi.org/10.1021/acs.est.4c03792

MacKenzie, D. (2009). Making things the same: Gases, emission rights and the politics of carbon markets. Accounting, Organizations and Society, 34(3-4), 440-455. https://doi.org/10.1016/j.aos.2008.02.004

Mateo-Márquez, A. J., González-González, J. M., & Zamora-Ramírez, C. (2022). An international empirical study of greenwashing and voluntary carbon disclosure. Journal of Cleaner Production, 363, 132567. https://doi.org/10.1016/j.jclepro.2022.132567

Matsumura, E. M., Prakash, R., & Vera-Muñoz, S. C. (2014). Firm-value effects of carbon emissions and carbon disclosures. The Accounting Review, 89(2), 695-724. https://doi.org/10.2308/accr-50629

Michaelowa, A., Shishlov, I., & Brescia, D. (2019). Evolution of international carbon markets: Lessons for the Paris Agreement. Wiley Interdisciplinary Reviews: Climate Change, 10(6), e613. https://doi.org/10.1002/wcc.613

Narassimhan, E., Gallagher, K. S., Koester, S., & Alejo, J. R. (2018). Carbon pricing in practice: A review of existing emissions trading systems. Climate Policy, 18(8), 967-991. https://doi.org/10.1080/14693062.2018.1467827

Newell, R. G., Pizer, W. A., & Raimi, D. (2013). Carbon markets 15 years after Kyoto: Lessons learned, new challenges. Journal of Economic Perspectives, 27(1), 123-146. https://doi.org/10.1257/jep.27.1.123

Paliwal, V., Chandra, S., & Sharma, S. (2020). Blockchain technology for sustainable supply chain management: A systematic literature review and a classification framework. Sustainability, 12(18), 7638. https://doi.org/10.3390/su12187638

Pástor, Ľ., Stambaugh, R. F., & Taylor, L. A. (2021). Sustainable investing in equilibrium. Journal of Financial Economics, 142(2), 550-571. https://doi.org/10.1016/j.jfineco.2020.12.011

Pedersen, L. H., Fitzgibbons, S., & Pomorski, L. (2021). Responsible investing: The ESG-efficient frontier. Journal of Financial Economics, 142(2), 572-597. https://doi.org/10.1016/j.jfineco.2020.11.001

Powell, W., Foth, M., Cao, S., & Natanelov, V. (2022). Garbage in garbage out: The precarious link between IoT and blockchain in food supply chains. Journal of Industrial Information Integration, 25, 100261. https://doi.org/10.1016/j.jii.2021.100261

Probst, B. S., Toetzke, M., Kontoleon, A., Díaz Anadón, L., Minx, J. C., Haya, B. K., Schneider, L., Trotter, P. A., West, T. A. P., Gill-Wiehl, A., & Hoffmann, V. H. (2024). Systematic assessment of the achieved emission reductions of carbon crediting projects. Nature Communications, 15, 9562. https://doi.org/10.1038/s41467-024-53645-z

Queiroz, M. M., Telles, R., & Bonilla, S. H. (2019). Blockchain and supply chain management integration: A systematic review of the literature. Supply Chain Management: An International Journal, 25(2), 241-254. https://doi.org/10.1108/SCM-03-2018-0143

Rejeb, A., Keogh, J. G., & Treiblmaier, H. (2019). Leveraging the internet of things and blockchain technology in supply chain management. Future Internet, 11(7), 161. https://doi.org/10.3390/fi11070161

Renneboog, L., Ter Horst, J., & Zhang, C. (2008). Socially responsible investments: Institutional aspects, performance, and investor behavior. Journal of Banking & Finance, 32(9), 1723-1742. https://doi.org/10.1016/j.jbankfin.2007.12.039

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research, 57(7), 2117-2135. https://doi.org/10.1080/00207543.2018.1533261

Schär, F. (2021). Decentralized finance: On blockchain- and smart contract-based financial markets. Federal Reserve Bank of St. Louis Review, 103(2), 153-174. https://doi.org/10.20955/r.103.153-74

Schneider, L., Duan, M., Stavins, R., Kizzier, K., Broekhoff, D., Jotzo, F., Winkler, H., Lazarus, M., Howard, A., & Hood, C. (2019). Double counting and the Paris Agreement rulebook. Science, 366(6462), 180-183. https://doi.org/10.1126/science.aay8750

Schneider, L., Kollmuss, A., & Lazarus, M. (2015). Addressing the risk of double counting emission reductions under the UNFCCC. Climatic Change, 131, 473-486. https://doi.org/10.1007/s10584-015-1398-y

Stavins, R. N. (1998). What can we learn from the grand policy experiment? Lessons from SO2 allowance trading. Journal of Economic Perspectives, 12(3), 69-88. https://doi.org/10.1257/jep.12.3.69

Stefan, M., & Wellenreuther, C. (2020). London vs. Leipzig: Price discovery of carbon futures during Phase III of the ETS. Economics Letters, 188, 108990. https://doi.org/10.1016/j.econlet.2020.108990

Streck, C. (2021). How voluntary carbon markets can drive climate ambition. Journal of Energy & Natural Resources Law, 39(3), 367-374. https://doi.org/10.1080/02646811.2021.1881275

Tang, D. Y., & Zhang, Y. (2020). Do shareholders benefit from green bonds? Journal of Corporate Finance, 61, 101427. https://doi.org/10.1016/j.jcorpfin.2018.12.001

Treiblmaier, H. (2018). The impact of the blockchain on the supply chain: A theory-based research framework and a call for action. Supply Chain Management: An International Journal, 23(6), 545-559. https://doi.org/10.1108/SCM-01-2018-0029

Trencher, G., Nick, S., Carlson, J., & Johnson, M. (2024). Demand for low-quality offsets by major companies undermines climate integrity of the voluntary carbon market. Nature Communications, 15, 6863. https://doi.org/10.1038/s41467-024-51151-w

Velte, P., Stawinoga, M., & Lueg, R. (2020). Carbon performance and disclosure: A systematic review of governance-related determinants and financial consequences. Journal of Cleaner Production, 254, 120063. https://doi.org/10.1016/j.jclepro.2020.120063

Vilkov, A., & Tian, G. (2023). Blockchain's scope and purpose in carbon markets: A systematic literature review. Sustainability, 15(11), 8495. https://doi.org/10.3390/su15118495

Wamba, S. F., Gunasekaran, A., Akter, S., Ren, S. J., Dubey, R., & Childe, S. J. (2017). Big data analytics and firm performance: Effects of dynamic capabilities. Journal of Business Research, 70, 356-365. https://doi.org/10.1016/j.jbusres.2016.08.009

West, T. A. P., Wunder, S., Sills, E. O., Börner, J., Rifai, S. W., Neidermeier, A. N., Frey, G. P., & Kontoleon, A. (2023). Action needed to make carbon offsets from forest conservation work for climate change mitigation. Science, 381(6660), 873-877. https://doi.org/10.1126/science.ade3535

Woo, J., Fatima, R., Kibert, C. J., Newman, R. E., Tian, Y., & Srinivasan, R. S. (2021). Applying blockchain technology for building energy performance measurement, reporting, and verification (MRV) and the carbon credit market: A review of the literature. Building and Environment, 205, 108199. https://doi.org/10.1016/j.buildenv.2021.108199

Yermack, D. (2017). Corporate governance and blockchains. Review of Finance, 21(1), 7-31. https://doi.org/10.1093/rof/rfw074

Zerbib, O. D. (2019). The effect of pro-environmental preferences on bond prices: Evidence from green bonds. Journal of Banking & Finance, 98, 39-60. https://doi.org/10.1016/j.jbankfin.2018.10.012

Zhang, D., Karplus, V. J., Cassisa, C., & Zhang, X. (2014). Emissions trading in China: Progress and prospects. Energy Policy, 75, 9-16. https://doi.org/10.1016/j.enpol.2014.01.022

Zhang, J., & Han, W. (2022). Carbon emission trading and equity markets in China: How liquidity is impacting carbon returns? Economic Research-Ekonomska Istraživanja, 35(1), 6466-6478. https://doi.org/10.1080/1331677X.2022.2049010