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From Technical Constraints to Institutional Choices: Navigating the Governance Trilemma of Blockchain in Green Trade

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Abstract

Sustainable trade requires verifiable, granular, and trustworthy data across multi-jurisdictional supply chains. This paper argues that blockchain' s binding constraints are institutional, not technical, and proposes the Green Trade Blockchain Governance Trilemma: no design can simultaneously maximize (i) transactional efficiency, (ii) regulatory verifiability, and (iii) decentralized governance with commercial privacy. Comparative cases—TradeLens, IBM Food Trust, Everledger, and Power Ledger—show divergent institutional choices and outcomes: TradeLens faltered under perceived hegemonic control; Food Trust succeeded via a buyer mandate; Everledger thrived through symbiosis with trusted authorities; Power Ledger scaled within a regulatory sandbox. We further analyze the Oracle Problem as the key limit to verifiability and assess privacy-enhancing technologies, especially zero-knowledge proofs, as partial mitigations that protect sensitive data while enabling compliance checks. We conclude that success hinges on context-specific institutional design—certified oracles plus verifiable computation—rather than a one-size-fits-all stack, offering actionable guidance for policymakers, consortia, and firms building credible green-trade infrastructure.

Keywords Blockchain governance; Green trade; Governance trilemma; Oracle problem; Zero-knowledge proofs

1 Introduction: The Data Demands of a Green World Trade

The global economy is at a critical juncture where the transition to sustainable development is no longer a peripheral issue but a central driver of international trade. This transformation is creating an unprecedented demand for a new data infrastructure capable of supporting global green trade. This infrastructure must be able to provide verifiable, granular, and highly credible information within intricate, multi-jurisdictional supply chains. In this context, blockchain technology, with its decentralized, immutable, and transparent characteristics, is seen as an ideal candidate for building this new infrastructure. However, a common misconception is to attribute the challenges of blockchain application in supply chains primarily to technical bottlenecks, such as scalability or interoperability. The core argument of this paper is that the most fundamental obstacle hindering blockchain from realizing its potential is not technical, but is deeply rooted in the inherent contradictions of governance and institutional design.

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The urgency of this challenge is most prominently highlighted by ambitious policy frameworks such as the European Green Deal[1, 2]. Through the implementation of two key regulations—the Carbon Border Adjustment Mechanism (CBAM) and the Corporate Sustainability Reporting Directive (CSRD)—the EU is fundamentally reshaping the global trade compliance landscape. CBAM requires importers to pay for the "embedded carbon emissions" in their imported products (such as cement, steel, and aluminum), effectively setting a cross-border price for carbon[3, 4, 5]. Meanwhile, CSRD significantly expands the scope and depth of corporate sustainability information disclosure, requiring nearly 50,000 companies to report not only on how sustainability issues affect their own financial situation but also on the specific impacts of their business activities on the environment and society, under the so-called "double materiality" principle[6, 7].

The common thread in these regulations is that they transform sustainability commitments, previously largely driven by corporate voluntarism and market reputation, into legally binding, third-party audited, and financially equivalent compliance obligations. This shift creates a massive "trust gap": regulators, investors, and consumers need a reliable mechanism to verify the sustainability data claimed by companies, data that often originates from the far upstream of global supply chains and whose authenticity is difficult to verify. Traditional supply chain management systems, based on paper documents and centralized databases, are ill-equipped to meet this demand for end-to-end, granular, and tamper-proof data.

It is against this backdrop that this paper proposes and aims to validate a "Governance Trilemma" analytical framework for blockchain applications in the green trade sector. This framework argues that any attempt to use blockchain technology to meet the data demands of green trade will face an unavoidable trade-off: among the following three ideal objectives, at most two can be achieved simultaneously.

The first objective is Transactional Efficiency: the platform's ability to reduce transactional friction, cut costs, and accelerate processes for commercial participants in the supply chain. The second is Regulatory Verifiability: the data provided by the system must be sufficiently transparent, auditable, and reliable to meet the stringent requirements of regulatory bodies (such as the EU authorities overseeing CBAM and CSRD). The third is Decentralized Governance & Commercial Privacy: the platform should be governed by a neutral, distributed model to prevent control by a single dominant party (whether a government or an industry giant), thereby encouraging broad competitor participation and protecting sensitive commercial data.

This paper contends that the success or failure of a blockchain project is not determined by the superiority of its technical architecture, but by the strategic choices its designers make when facing this governance trilemma. Through an in-depth analysis of the subsequent case studies, this research will demonstrate that it is these institutional decisions about priorities that ultimately determine whether a platform thrives or becomes an abandoned 'digital island'.

2 The Trilemma: An Analytical Framework for Global Economic Governance

The "trilemma" or "impossible trinity" has proven to be a powerful analytical tool for dissecting complex global governance systems. Its core idea is to reveal the inherent constraints within a policy space: out of three equally desirable goals, policymakers cannot fully achieve all of them simultaneously and must make trade-offs. Placing the governance trilemma proposed in this paper within this long-standing academic lineage not only highlights its theoretical rigor but also reveals its deep roots in the evolution of global economic governance.

2.1 Fundamental Concepts in Political Economy

The classic prototype of the trilemma framework is the "Impossible Trinity" in macroeconomics, also known as the Mundell-Fleming Model[8, 9, 10]. This theory states that a country cannot simultaneously achieve the following three policy objectives: (1) a fixed exchange rate system; (2) free movement of capital; and (3) an independent monetary policy[8]. For example, to maintain a fixed exchange rate and allow free capital flow, the country's central bank must relinquish the power to set independent interest rate policies; its monetary policy must serve the goal of exchange rate stability. This framework clearly illustrates the fundamental trade-offs faced by open economies in their policy choices.

Dani Rodrik elevated this analytical paradigm from the realm of monetary policy to the macro level of global political economy, proposing the influential "Political Trilemma of the World Economy"[11, 12, 13]. Rodrik argues that there is an irreconcilable conflict among (1) deep economic integration (or hyper-globalization), (2) national sovereignty, and (3) democratic politics, and any nation can only choose two of the three[14]. For instance, if a country wishes to deeply integrate into the global market (hyper-globalization) while maintaining its national sovereignty, it must limit the interference of domestic democratic politics in economic policy, a situation known as the "Golden Straitjacket," because the rules of the global market may conflict with the will of domestic voters. Conversely, to uphold both national sovereignty and democratic politics, barriers must be set against globalization to protect domestic policy space. Rodrik's framework is the direct theoretical source for the governance trilemma proposed in this paper, as there are profound parallels in their logical structures.

2.2 A Technical Preamble: Distinguishing Governance from Engineering

Before delving into the governance-level dilemma, it is necessary to distinguish it from technical-level challenges. The "Blockchain Trilemma," proposed by Ethereum founder Vitalik Buterin, is key to understanding this distinction[15, 16]. This theory describes the trade-offs faced by the underlying technical architecture of a blockchain, namely that the three technical properties of (1) decentralization, (2) security, and (3) scalability are difficult to optimize simultaneously[15]. For example, to achieve higher transaction processing speeds (scalability), some blockchain designs may reduce the number of validating nodes, which in turn compromises their degree of decentralization and security. Buterin's trilemma focuses on the engineering design at the protocol layer, whereas this paper focuses on the socio-political governance arrangements built on top of these technologies. Although the two are interrelated—technical choices can influence governance possibilities—the core of this paper is to analyze how governance-level conflicts persist even if technical problems are perfectly solved.

2.3 The Governance Trilemma of Blockchain in Green Trade

Building on the theoretical foundations above, this paper formally introduces the governance trilemma framework for analyzing blockchain applications in the green trade sector. Its three vertices are specifically defined as follows.

The first is Transactional Efficiency: This is the core business-driven objective. A successful platform must be able to significantly optimize existing processes, for example, by automating document handling, reducing intermediary steps, speeding up customs clearance, and lowering compliance costs, thereby creating tangible economic value for participating enterprises. If a system is technologically advanced but cumbersome and expensive to use, it will fail to gain commercial traction.

The second is Regulatory Verifiability: This is the core policy-driven objective. In the context of green trade, the platform's data must be able to serve as legal evidence for compliance with regulations like CBAM and CSRD. This means the data must not only be immutably recorded, but its source and quality must also be trusted and verifiable by regulators and third-party auditors. This requires the system to have a high degree of transparency, robust auditing capabilities, and seamless integration with regulatory frameworks.

The third is Decentralized Governance & Commercial Privacy: This is the core objective for achieving broad participation and maintaining long-term vitality. In an ecosystem composed of competing enterprises, any platform dominated by a single entity (especially a market leader) will arouse widespread suspicion. Competitors will worry that their sensitive commercial data (such as pricing, customer relationships, and supply chain layouts) could be accessed by the dominant party. Therefore, a neutral, distributed governance structure is a prerequisite for building trust and encouraging data sharing. At the same time, the system must provide strong privacy protection mechanisms to ensure that participants can protect their commercial secrets while sharing necessary compliance data.

These three objectives have profound internal tensions. For example, maximizing regulatory verifiability might require complete transparency, which would directly undermine commercial privacy. To achieve the highest transactional efficiency, having a powerful centralized entity enforce uniform standards might be the quickest path, but this would destroy decentralized governance. It is these unavoidable trade-offs that constitute the governance dilemma for blockchain applications in green trade.

This analytical framework is contextualized within a broader typology of trilemmas across economics and technology. The classic "Impossible Trinity," attributed to Mundell-Fleming in macroeconomics, posits that a nation cannot simultaneously maintain a fixed exchange rate, allow free capital movement, and have an independent monetary policy. Elevating this concept to global political economy, Dani Rodrik's "Political Trilemma of the World Economy" asserts the incompatibility of deep economic integration, national sovereignty, and democratic politics. In the realm of computer science, Vitalik Buterin's "Blockchain Trilemma" highlights the technical trade-offs among decentralization, security, and scalability. The "Governance Trilemma" proposed in this paper situates itself within green trade and institutional economics, identifying the core conflict among transactional efficiency, regulatory verifiability, and decentralized governance with commercial privacy.

This comparison reveals a deeper connection: the governance trilemma proposed in this paper is, in a sense, a micro-level institutional manifestation of Rodrik's macro-political trilemma. The choices made by companies and consortia when designing trade blockchain platforms are essentially localized negotiations of the fundamental tensions between integration, sovereignty, and democratic control that nations face on a larger scale. In this correspondence, "transactional efficiency" can be seen as a proxy for "deep economic integration," aiming for the frictionless integration of the economic system. "Regulatory verifiability" corresponds to "national sovereignty" (in this case, the supranational sovereignty of the EU), which is the ability of a governing body to impose its rules and standards on the system. "Decentralized governance" is analogous to "democratic politics," aimed at preventing the arbitrary control of a single entity and ensuring that the platform's participants—the 'community'—have a voice. Therefore, the effort to design a viable green trade blockchain platform is not just a commercial or technical problem; it is a microcosm of the fundamental political challenges facing 21st-century global economic governance. This understanding elevates the analysis of this paper from a narrow technical application area to a broader commentary on global economic governance.

3 The New Institutional Environment: The EU Green Deal's Data Mandates

The value of any technological solution is determined by the nature and severity of the problem it aims to solve. For blockchain applications in green trade, this "problem" is being defined with unprecedented force and clarity by the European Union. The EU's Green Deal is not a vague set of aspirations but a new, data-driven trade paradigm being enforced globally through a series of legally binding regulations. This section will delve into the specific requirements of these regulations to precisely outline the institutional needs that any blockchain solution must meet.

3.1 Carbon Border Adjustment Mechanism (CBAM): Quantifying Embedded Emissions

CBAM is the "enforcement arm" of the EU's climate policy, with its core objective being to address "carbon leakage"—the phenomenon where companies in the EU relocate production to countries with laxer environmental standards due to strict carbon pricing policies, resulting in no net reduction in global emissions. According to Regulation (EU) 2023/956, CBAM provides a direct solution to this problem[3].

The mechanism's implementation is divided into two phases. The transitional period began on October 1, 2023, and will last until December 31, 2025[17, 18]. During this time, importers' main obligation is reporting; they must submit quarterly reports detailing the direct and indirect emissions embedded in specific imported goods such as cement, steel, aluminum, fertilizers, electricity, and hydrogen[19]. This phase involves no financial payments and is primarily intended to collect data and familiarize all stakeholders with the new reporting process.

From January 1, 2026, CBAM will enter its definitive implementation phase[20]. At that point, importers will be required to purchase and surrender a corresponding number of "CBAM certificates" for the embedded emissions of their imported goods each year. The price of these certificates will be linked to the auction price of carbon allowances in the EU Emissions Trading System (EU ETS)[21]. The essence of this mechanism is to extend the EU's carbon price to its borders, ensuring that imported products bear the same carbon costs as domestically produced ones.

CBAM places extremely stringent demands on data infrastructure. It no longer accepts broad, corporate-level emissions reports but requires product-level, precise emissions data that is traceable to the source of production. For example, to account for the embedded emissions of a batch of imported steel, one would need to know the source of the electricity used in its production (whether from coal-fired power or renewable energy), the specific production processes, and the carbon footprint of the raw materials. This creates a direct need for an immutable and auditable data chain starting from the point of production. Any blockchain platform designed to serve CBAM compliance must be able to capture, transmit, and verify this highly technical and granular data.

3.2 Corporate Sustainability Reporting Directive (CSRD): The Double Materiality Principle

If CBAM is a "surgical strike" targeting specific high-carbon products, then CSRD is a "systemic transformation" covering the entire economic system. CSRD replaces the previous Non-Financial Reporting Directive (NFRD) and dramatically expands the number of regulated companies from about 11,700 to nearly 50,000[22, 23, 24].

The core innovation of CSRD is the introduction and mandatory enforcement of the "double materiality" principle[25, 26, 27]. This principle requires companies to disclose information from two perspectives. The first is Financial Materiality ('outside-in'), which involves assessing how sustainability issues like climate change and resource depletion pose risks or opportunities to the company's financial condition, performance, and development prospects. This continues the traditional risk management perspective. The second is Impact Materiality ('inside-out'), which involves assessing the actual or potential significant impacts of the company's own operations and its upstream and downstream value chain activities on the environment (e.g., greenhouse gas emissions, biodiversity loss) and people (e.g., labor rights, community impacts)[28].

The revolutionary nature of the "double materiality" principle is that it forces companies to be accountable for and report on the externalities of their entire value chain. A clothing company must not only report on the risks that climate change may pose to its cotton supply chain but also on the water consumption and labor rights protection of its suppliers during production. This requires an unprecedented level of supply chain visibility, extending far beyond a company's own operational boundaries. Furthermore, CSRD mandates that these sustainability reports must be third-party audited, with a level of rigor comparable to financial audits[6].

3.3 The Broader Digital Governance Ecosystem

CBAM and CSRD do not exist in isolation; they are part of the EU's broader digital governance strategy. The Data Act, which will be fully effective on September 12, 2025, aims to promote fair access to and use of data, specifically granting users (including businesses and consumers) the right to access and share data generated by the connected devices (Internet of Things, IoT) they use[29, 30]. This is significant for green trade as it provides a legal basis for the automated and credible collection of primary emissions data via IoT devices (such as factory sensors and smart meters). Meanwhile, the AI Act sets rules for the use of algorithms in these platforms for data analysis and verification, ensuring their reliability and accountability[31].

In summary, the combination of CBAM and CSRD creates a "pincer movement" on supply chains. CBAM demands deep, product-level carbon data, while CSRD requires broad, entity-level ESG impact data. A truly effective digital solution must be able to serve both needs simultaneously, meaning it must be capable of aggregating granular product data (for CBAM) into comprehensive corporate-level reports (for CSRD). For instance, the energy consumption data collected for a batch of imported aluminum is both the basis for calculating CBAM tariffs and a key component of the company's CSRD report on Scope 3 emissions and its climate transition plan. This dual demand significantly increases the complexity and strategic importance of platform design, and also provides a vast stage for technologies like blockchain that can integrate and verify heterogeneous data from multiple sources.

4 Empirical Analysis: Navigating the Trilemma in Practice

The value of a theoretical framework ultimately depends on its ability to explain real-world phenomena. This section will validate the effectiveness of the governance trilemma framework proposed earlier through a structured comparative analysis of four representative blockchain application cases. These four cases—two failures and two relative successes—each represent a unique strategic choice made within the trade-off space of the trilemma. The analysis will reveal how these choices directly led to their respective fates, thus tightly linking abstract theory with concrete business practices.

4.1 The Failure of a Global Platform: TradeLens and the Dominator's Dilemma

Launched jointly in 2018 by shipping giant Maersk and tech giant IBM, TradeLens was one of the most ambitious blockchain attempts in the supply chain sector to date. Its goal was to create an open, neutral global trade digitalization platform to enhance efficiency, security, and transparency. From the perspective of the trilemma, TradeLens clearly positioned transactional efficiency (through digitized documents and process automation) and regulatory verifiability (by providing credible cargo tracking records) as its core value propositions.

However, the project was announced to be discontinued on November 29, 2022, and was completely shut down by the end of the first quarter of 2023[32, 33, 34]. The official reasons given were that the platform failed to achieve "the necessary commercial viability" and that "full global industry collaboration was not achieved"[35]. A deeper analysis reveals that the root of its failure lies precisely at the third vertex of the trilemma: decentralized governance and commercial privacy.

Although TradeLens was technically feasible, its governance model was fundamentally flawed from the outset. The platform was led by Maersk, the world's largest container shipping company, which made all its potential partners—namely Maersk's direct competitors (such as CMA CGM, Hapag-Lloyd, etc.)—deeply suspicious of its "neutrality"[35]. These companies were extremely reluctant to upload their most sensitive commercial data, including customer information, shipping routes, pricing strategies, and vessel utilization rates, to a platform controlled by their biggest rival. As one industry expert noted, the "lack of buy-in" from key industry stakeholders was a core factor in its failure, as they were "unwilling to share data with a for-profit entity"[32]. The lack of trust in its governance structure ultimately prevented the platform from attracting the "critical mass" of participants needed to achieve network effects.

The TradeLens case is a classic failure of attempting to achieve all three vertices of the trilemma simultaneously. While pursuing efficiency and verifiability, it claimed to be an "open and neutral" decentralized platform. However, the market's reaction showed that a consortium led by an industry hegemon cannot be perceived as truly decentralized. The market voted with its feet, rejecting its centralized governance model, which ultimately led to the collapse of the entire project. This proves that in a highly competitive industry, governance neutrality is not an optional extra but a prerequisite for a platform's survival.

4.2 The Success of a Walled Garden: IBM Food Trust and the Walmart Mandate

In stark contrast to TradeLens's open platform strategy is another of IBM's blockchain projects—Food Trust. This project has achieved remarkable success in the field of food traceability, and the key lies in a completely different strategic trade-off. Food Trust proactively abandoned the pursuit of decentralized governance, instead adopting a top-down, mandatory adoption model driven by a core enterprise in the ecosystem.

This core enterprise is Walmart, the world's largest retailer. Faced with frequent food safety incidents, Walmart urgently needed a tool that could quickly and accurately trace the source of contaminated food. In a pilot project with IBM, blockchain technology demonstrated astonishing capabilities: a test to trace the origin of a batch of mangoes was reduced from the traditional 6 days, 18 hours, and 26 minutes to a stunning 2.2 seconds[36].

Following this successful pilot, Walmart made a decisive move: it issued a mandate to all its suppliers of fresh leafy greens, requiring them to join the IBM Food Trust platform and upload traceability data as required within a specified deadline[37, 38, 39]. For these suppliers, joining the platform was not an option but a prerequisite for continuing to do business with Walmart. This "Walmart mandate" effectively solved the common "chicken-and-egg" problem that blockchain platforms face in their initial stages, quickly achieving coverage of key participants within Walmart's supply chain ecosystem. This ensured the platform's transactional efficiency (for Walmart, the efficiency of rapid traceability) and regulatory verifiability (meeting food safety regulatory requirements).

The success of IBM Food Trust is a typical case of maximizing two vertices at the expense of a third. It abandoned decentralized governance and accepted a centralized model dominated by Walmart, a "benevolent dictator." The suppliers put on what Rodrik called the "Golden Straitjacket": by accepting the rules of the dominant player, they gained access to its vast market (efficiency) and met its stringent requirements (verifiability), but at the cost of losing their autonomy of choice. This shows that in industries with one or a few core enterprises holding absolute market power, a centralized "walled garden" model is a viable institutional choice.

4.3 Symbiosis in a Niche Market: The Everledger Model

Everledger, founded in 2015, demonstrates a third way of navigating the trilemma[40, 41, 42]. It did not attempt to build an all-encompassing global platform like TradeLens, nor did it rely on the coercive power of a single giant like IBM Food Trust. Instead, Everledger chose a high-value niche market—diamonds, art, and luxury goods—and adopted a strategy of symbiosis with existing governance structures.

In the diamond industry, provenance and anti-counterfeiting are core pain points. The industry already has a global governance framework, the Kimberley Process Certification Scheme (KPCS), aimed at eliminating the trade of "conflict diamonds" (blood diamonds)[43, 44, 45]. However, the Kimberley Process relies on paper certificates, which are easy to forge and lose. Everledger's entry point was not to replace the Kimberley Process but to provide a digital, more secure supplementary layer for it.

The key to Everledger's success lies in its deep collaboration with established "trust anchors" in the industry, such as the Gemological Institute of America (GIA), the world's most authoritative diamond grading institution[46, 47, 48]. When the GIA issues a physical grading report for a diamond, Everledger creates a corresponding, immutable "digital twin" on the blockchain, recording its 4C standards (carat, color, clarity, cut) and the GIA certificate information. This model skillfully balances the trilemma. For regulatory verifiability, by binding to the certifications of authoritative bodies like the GIA, the platform's data credibility is endorsed by the existing system. For transactional efficiency, a secure and convenient digital identity record greatly enhances efficiency and security in the circulation, insurance, and secondary trading of diamonds. For decentralized governance, Everledger acts as a neutral technology service provider; it does not try to set industry rules but provides technical support for existing ones. Its governance problem is confined to a well-defined community, thus avoiding the global governance challenges faced by TradeLens.

Everledger has carved out a "middle path." It achieves verifiability by attaching itself to existing trusted institutions, provides efficiency within its niche market, and manages governance issues by acting as a neutral technology layer. This suggests that for some industries, the best role for blockchain may not be as a disruptor but as an "enhancer" and "digital coordinator" for existing trust systems.

4.4 A Green Application Case: Power Ledger and Peer-to-Peer Energy Markets

The pilot project by the Australian company Power Ledger in Uttar Pradesh, India, provides a direct illustration of the trilemma's application in the green energy sector. The project uses blockchain technology to create a peer-to-peer (P2P) energy trading platform between "prosumers" with rooftop solar installations and regular electricity consumers.

The project's success was due to a key institutional arrangement: it was conducted in a "regulatory sandbox" environment[49]. This meant that the regulatory authority (the Uttar Pradesh Electricity Regulatory Commission) provided policy support and exemptions for this innovative project, allowing it to test new business models and technologies in a real-world setting without immediately having to comply with all existing regulations.

This favorable institutional environment greatly eased the tensions of the trilemma. The pilot project achieved significant results: it not only successfully validated the feasibility of P2P energy trading but also brought tangible economic benefits to participants—the market price for electricity purchased through the platform was 43% lower than the traditional retail electricity price[50]. This achievement directly spurred institutional change: after the pilot concluded, the local regulatory authority officially issued a new tariff order, paving the way for the statewide rollout of P2P trading[51].

The Power Ledger case demonstrates that a favorable and adaptive institutional environment can be a catalyst for resolving the governance trilemma. The active support of the government provided the platform with legitimacy and regulatory verifiability. Clear economic benefits (cheaper electricity) drove widespread user adoption, achieving transactional efficiency. And the focused nature of the specific application scenario—P2P trading—allowed a relatively simple decentralized model to operate effectively. This shows that when technological innovation and institutional innovation advance in tandem, the trade-offs of the trilemma can be managed more effectively.

The analysis of these practical outcomes reveals distinct strategic paths. For TradeLens, the goal was high transactional efficiency and high regulatory verifiability. However, it was perceived as having low decentralized governance. Its key strategy was a global consortium led by an industry leader aiming to set open standards. The result was failure, as competitors distrusted its governance model, leading to a lack of widespread adoption. For IBM Food Trust, it achieved high transactional efficiency within its ecosystem and high regulatory verifiability by meeting buyer requirements. Its decentralized governance was extremely low, being highly centralized. The strategy was a top-down mandate from a core buyer with market power (Walmart). This led to success, with rapid deployment and value verification within a closed supply chain ecosystem. For Everledger, it has medium-to-high transactional efficiency in its niche market and high regulatory verifiability through symbiosis with authoritative bodies. Its decentralized governance is also medium-to-high, acting as a neutral technology layer. Its strategy involved attaching to and enhancing existing industry trust institutions (like the GIA) and serving as a technology provider. This was successful, establishing a viable business model in high-value niche markets like diamonds. For Power Ledger, it achieved high transactional efficiency by significantly cutting costs, high regulatory verifiability due to regulatory support, and high decentralization with its P2P model. The key strategy was piloting within a 'regulatory sandbox,' aligning technological and institutional innovation. This resulted in success, validating the business model and directly driving favorable regulatory changes.

This summary clearly shows that no single case managed to score high on all three dimensions perfectly. The successful ones made clear trade-offs: IBM Food Trust sacrificed decentralization, Everledger focused on institutional symbiosis in a specific context, and Power Ledger benefited from external institutional support. The failure of TradeLens stemmed from its strategic ambiguity of trying to "have it all," ultimately foundering on the rocks of governance. This provides strong empirical support for the paper's core thesis: institutional choices, not technology itself, determine success or failure.

5 Reconciling Trade-offs: Institutional Choices and Technological Mitigation

From the analysis of the cases above, a clear conclusion emerges: there is no "technical fix" that can solve the governance trilemma once and for all. The core of the solution lies in making conscious institutional choices—that is, explicitly prioritizing which vertex of the trilemma to focus on based on the specific application scenario and industry structure. However, this does not mean that technology is irrelevant. This section will further explore how emerging technologies, particularly privacy-enhancing technologies, while unable to eradicate the trilemma, can significantly mitigate its most acute conflicts, thereby expanding the space of possible institutional choices.

5.1 The Enduring Challenge of the Physical-Digital Divide: The Oracle Problem

Before discussing technological mitigation solutions, it is essential to confront a fundamental limitation of blockchain when applied to the real world: "The Oracle Problem"[52, 53]. The core strength of blockchain is guaranteeing the integrity and immutability of on-chain data. Once data is written to the blockchain, one can be certain it has not been tampered with. However, the blockchain itself cannot verify the authenticity of this data before it is written. It is like an absolutely honest bookkeeper who faithfully records everything they are told, but if they are told a lie, they will faithfully record that lie.

An "oracle" is the entity or mechanism responsible for feeding external world (off-chain) data onto the blockchain (on-chain)[54, 55]. In the context of green trade, an IoT sensor in a factory, a carbon emissions report from a third-party audit firm, or a data interface from a customs system all act as oracles. The oracle problem thus becomes the Achilles' heel of regulatory verifiability[56]. If a factory's sensor is manipulated, or a supplier submits fraudulent emissions data, the blockchain will only immutably and permanently record this fraudulent data.

The profound implication of this problem is that technology cannot completely replace institutional trust. We cannot simply "trust the blockchain"; rather, we must trust the oracles that provide data to the blockchain. Therefore, the challenge of building a credible green trade data platform shifts from "how to ensure on-chain data is not tampered with" to "how to ensure the off-chain data input into the blockchain is authentic and reliable." The latter is an institutional design problem, involving the certification of data sources (like sensors), the accreditation of data providers (like audit firms), and penalty mechanisms for data fraud.

5.2 A Path to Reconciliation? Privacy-Enhancing Technologies

While the oracle problem reveals the limitations of technology, another class of technologies—Privacy-Enhancing Technologies (PETs)—demonstrates its potential. In the governance trilemma, the conflict between regulatory verifiability and commercial privacy is particularly pronounced. Regulators demand transparent and auditable data, while businesses want to protect their commercial secrets. Zero-Knowledge Proofs (ZKPs) are one of the most promising technologies for resolving this conflict.

A Zero-Knowledge Proof is a cryptographic protocol that allows one party (the Prover) to prove to another party (the Verifier) that a statement is true, without revealing any information beyond the validity of the statement itself[57, 58]. Its core properties include Completeness, meaning if the statement is true, an honest prover can always convince the verifier; Soundness, meaning if the statement is false, a cheating prover has a negligible probability of convincing the verifier; and Zero-Knowledge, meaning if the statement is true, the verifier learns nothing other than the fact that the statement is true[57].

Applying ZKPs to the green trade trilemma, one can imagine the following scenario: an electric vehicle manufacturer needs to prove to EU regulators that its batteries meet sustainable sourcing standards (e.g., cobalt is not from conflict mines, and production carbon emissions are below a certain threshold). Without ZKPs, the manufacturer might have to submit its complete supply chain data, including supplier lists, procurement prices, and production process parameters—all highly sensitive commercial secrets. This would severely compromise its commercial privacy. With ZKPs, the manufacturer can use all its supply chain data as secret inputs to run a computation that verifies compliance. It then submits a ZKP to the regulator. This proof cryptographically guarantees that the conclusion "the battery meets sustainability standards" is correct, but the entire process reveals no details about suppliers, prices, or processes.

In this way, ZKPs build a bridge directly between regulatory verifiability and commercial privacy. The regulator gets the mathematically verifiable assurance of compliance they need, while the business protects the commercial secrets it depends on for survival. This greatly mitigates one of the most central trade-offs of the trilemma, opening the door for businesses that were hesitant to participate in platforms due to data sensitivity.

However, ZKPs do not solve all problems. Notably, ZKPs cannot solve the oracle problem. A ZKP can only guarantee that the computation process based on a given input is correct; it cannot guarantee that the input itself is true. If the raw data input into the ZKP computation (e.g., carbon emissions data from a supplier) is falsified, the ZKP will only faithfully perform a 'correct' computation on this falsified data and generate a misleading proof.

This leads to a more nuanced and realistic conclusion: the combination of the oracle problem and ZKPs reveals a key distinction between the integrity of data origination and the privacy of data computation. Technology (like ZKPs) can solve the latter very well, but the former still heavily relies on institutional trust and verification.

Therefore, a credible future green trade system is likely to be a hybrid system that deeply integrates institutions and technology, rather than a purely technological utopia. Its logic might be as follows: first, ensure the credibility of "oracles" (data sources) through institutional design (e.g., government certification, industry standards, third-party audits). Then, input this data from trusted sources into a blockchain-based platform. Finally, use PETs like ZKPs to allow participants to compute, share, and verify this data while protecting commercial privacy to meet regulatory requirements. The ultimate trust model is not simply "trust the blockchain," but "trust certified oracles, and verify computations based on their data using ZKPs on the blockchain." This more mature and pragmatic vision points the way for policymakers and system designers to strike a balance between technological possibilities and institutional realities.

6 Conclusion: The Future of Trust in Global Trade

This study began with a core thesis: in building the digital infrastructure for the emerging global green trade system, the most severe challenges are not technological but stem from inherent conflicts in governance and institutional design. To systematically analyze this challenge, this paper constructed and validated a "Green Trade Blockchain Governance Trilemma" framework, positing an unavoidable trade-off among transactional efficiency, regulatory verifiability, and decentralized governance and commercial privacy.

Through an in-depth comparative analysis of four cases—TradeLens, IBM Food Trust, Everledger, and Power Ledger—this research has provided strong empirical support for the framework's validity. The analysis shows that a project's success or failure is directly related to its strategic positioning within the trilemma space. TradeLens attempted to achieve all objectives simultaneously, but its governance model, dominated by an industry giant, failed to gain market trust, ultimately leading to its demise. In contrast, successful projects made clear institutional choices: IBM Food Trust succeeded within a closed ecosystem by sacrificing decentralization and leveraging the market power of a core buyer for mandatory adoption; Everledger found balance in a niche market through symbiosis with existing authorities; and Power Ledger's success highlighted the critical role of an adaptive regulatory environment (a regulatory sandbox) in catalyzing innovation. These cases collectively demonstrate that there is no one-size-fits-all "best practice"; successful paths are diverse and highly dependent on specific industry structures and institutional contexts.

The study further explored the possibilities and limitations of reconciling the trilemma's conflicts. On one hand, the "oracle problem" reveals a fundamental limitation of technology—blockchain cannot independently verify the authenticity of off-chain data—underscoring the indispensability of institutional efforts (such as certification and auditing) to establish trusted data sources. On the other hand, privacy-enhancing technologies like Zero-Knowledge Proofs (ZKPs) offer powerful technical tools to mitigate the core conflict between "regulatory verifiability" and "commercial privacy," although they too cannot solve the problem of trust at the data source. This leads to a central conclusion: future solutions will inevitably be hybrids of deeply integrated technology and institutions, with a trust foundation based on "certified oracles + verifiable computation."

Based on these findings, this study offers the following actionable recommendations for decision-makers in different fields. For policymakers, the primary task is to create an institutional environment conducive to innovation. Instead of trying to pick specific technology platforms as "champions," they should learn from the Power Ledger case and actively promote "regulatory sandbox" models to provide experimental grounds for new technologies and business models[49]. Policy should focus on setting uniform data standards, certifying credible "oracles" (such as data audit firms and IoT device standards), and establishing clear legal liability frameworks, thereby providing a fair and transparent competitive arena for market-driven solutions.

For industry consortia, the lessons from TradeLens's failure must be heeded. When building industry-level platforms, governance structure design is paramount. Neutral, transparent, and broadly representative governance mechanisms, such as establishing an independent non-profit foundation to operate the platform, should be established from the project's inception. Clear rules, fair benefit-sharing mechanisms, and robust data privacy protections are prerequisites for persuading competitors to lower their guard and collaborate.

For corporate strategists, the illusion of finding a perfect, one-size-fits-all solution should be abandoned in favor of making sober strategic choices based on their position in the value chain and specific business needs. If you are a dominant buyer like Walmart, you can consider adopting a top-down mandatory adoption model to quickly realize value within your own supply chain ecosystem. If you are an innovator in a niche market with mature trust institutions, you can follow Everledger's example and adopt a strategy of symbiosis with existing systems, becoming an "enhancer" of the current trust framework. If you are in a specific application area with a friendly regulatory environment and clear economic incentives, you can collaborate with like-minded partners to iterate quickly in a focused scenario, much like Power Ledger.

In conclusion, transforming the global trading system towards a green and sustainable future is a grand undertaking that involves a deep reconstruction of trust. Digital technologies like blockchain provide unprecedentedly powerful tools for this task, but they are not the answer in themselves. As history has repeatedly shown, the full potential of technology can only be unleashed if we can design wise and prudent institutional arrangements to match. The art of navigating governance, not just mastering technology, will determine whether we can successfully build a truly trustworthy, efficient, and sustainable future for global trade.

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