Green Ledgers, Heavy Footprints: Reconciling Blockchain's Energy Costs with ESG-Driven Sustainable Supply Chain Financing

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Abstract

Blockchain technology is increasingly promoted as core infrastructure for ESG-driven sustainable supply chain finance, where its transparency and traceability can make environmental and social claims verifiable and broaden access to financing. Yet the proof-of-work blockchains that dominate public attention consume enormous amounts of energy, with a correspondingly large carbon footprint and a growing stream of electronic waste, raising the possibility that a technology adopted to advance sustainability may instead undermine it. This article confronts that paradox and asks whether, and under what conditions, blockchain's energy costs can be reconciled with the ESG goals of sustainable supply chain finance. We develop a net-ESG-impact accounting framework that places the transparency and financing benefits of a blockchain deployment on a common footing with its energy, carbon, and e-waste costs, and we synthesise evidence from the operations, finance, and energy literatures into a set of illustrative analyses across deployment archetypes. The analysis shows that energy intensity is a property of the consensus mechanism rather than of distributed ledgers as such: public proof-of-work deployments can be net-negative, while proof-of-stake, layer-two, and permissioned deployments are strongly net-positive. Reconciliation is therefore achievable as a design and governance choice, provided that sustainable-finance reporting begins to account for the energy intensity of its own digital infrastructure.

Keywords: Blockchain; sustainable supply chain finance; ESG; energy consumption; proof-of-work; proof-of-stake; carbon footprint; distributed ledger technology

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1. Introduction

Blockchain technology has moved from a niche cryptographic curiosity to a serious instrument of supply chain governance and finance. By maintaining a shared, append-only ledger that no single party controls, a blockchain can record the provenance, custody, and condition of goods as they move through a multi-tier supply chain, and it can anchor the financial instruments that fund that movement to verifiable physical events rather than to unverifiable assertions. For sustainable supply chain finance in particular, the appeal is acute. Lenders, buyers, and regulators increasingly demand evidence that the environmental, social, and governance (ESG) claims attached to a product or a borrower are real, and a tamper-evident ledger appears to supply exactly the kind of evidence that conventional paper trails cannot (Saberi et al., 2019). It is therefore unsurprising that blockchain has been proposed as core infrastructure for green trade finance, for ESG-linked lending, and for the traceability systems on which both depend (Yang et al., 2025).

Yet the same technology carries an uncomfortable contradiction at its centre. The best-known blockchains secure their ledgers through proof-of-work, a consensus mechanism that deliberately consumes enormous quantities of electricity as the price of decentralised trust. Estimates place the electricity demand of the Bitcoin network alone on the order of a mid-sized industrial economy, with a correspondingly large carbon footprint and a growing stream of electronic waste from specialised mining hardware (de Vries, 2018; Stoll et al., 2019; de Vries & Stoll, 2021). A system promoted as a tool for advancing the environmental pillar of ESG may, depending on how it is built, impose an environmental cost that swamps the benefits it delivers. This is the paradox captured in the title of this article: the green ledger can carry a heavy footprint, and a financing instrument designed to certify sustainability can quietly undermine it.

This article confronts that paradox directly and asks whether, and under what conditions, blockchain's energy costs can be reconciled with the ESG goals of sustainable supply chain finance. We argue that the contradiction is real but not inherent. The energy intensity that dominates public discussion is a property of one family of consensus mechanisms, not of distributed ledgers as such; alternative designs reduce energy consumption by many orders of magnitude while preserving most of the transparency and traceability benefits that matter for supply chain finance (Sedlmeir et al., 2020). The central task is therefore not to accept or reject blockchain wholesale but to assess its **net** ESG impact, defined as the value it creates through transparency and improved financing minus the environmental cost it imposes through energy use, carbon emissions, and hardware waste, and to identify the design and governance choices that move that net impact from negative to strongly positive.

Figure 1 sets out the conceptual structure of the paradox that organises the analysis. A single blockchain-based supply chain finance platform gives rise to two divergent consequences. On one side it creates ESG value, principally through the transparency and traceability of supply chain flows and through cheaper and broader access to financing for firms that can now credibly signal their quality and their compliance. On the other side it incurs an environmental cost, principally through the energy consumed by its consensus mechanism and through the carbon emissions and electronic waste that follow from that energy use. The net ESG impact of the green ledger is the balance of these two arms, and the thesis of this article is that the sign and magnitude of that balance are determined by choices that are open to designers, adopters, and the institutions that govern sustainable finance.

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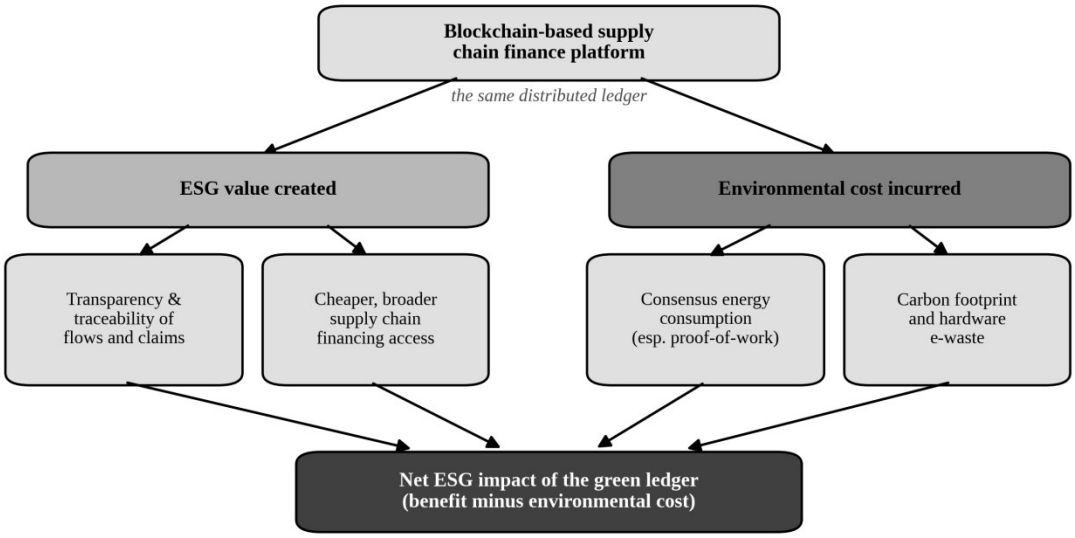


Figure 1. Conceptual Framework of the Green-Ledger Paradox

Note. Conceptual framework of the green-ledger paradox, in which a single blockchain-based supply chain finance platform simultaneously creates ESG value through transparency and financing and incurs an environmental cost through consensus energy use, carbon emissions, and e-waste, with the net ESG impact determined by the balance between the two.

The contribution of the article is fourfold. First, it brings together two literatures that have largely developed in isolation: the operations and finance literature on blockchain for supply chain management and finance, which tends to emphasise benefits, and the energy and environmental science literature on cryptocurrency energy consumption, which tends to emphasise costs. Second, it proposes a net-ESG-impact accounting framework that places benefit and cost on a common footing so that the two can be compared rather than asserted separately. Third, it synthesises quantitative evidence from across these literatures into a set of illustrative analyses that show how net impact varies across blockchain deployment archetypes. Fourth, it derives concrete reconciliation pathways and situates them within the governance of sustainable finance, arguing that ESG reporting must begin to account for the energy intensity of the digital infrastructure on which it increasingly relies. The remainder of the article proceeds as follows. Section 2 reviews the relevant literature. Section 3 develops the conceptual framework and the net-ESG-impact accounting approach. Section 4 examines the energy cost of blockchain architectures, and Section 5 the ESG value created in supply chain finance. Section 6 presents a data-driven reconciliation analysis across deployment archetypes. Section 7 discusses implications, pathways, and future directions, and Section 8 concludes.

2. Literature Review

The argument of this article sits at the intersection of four research streams: blockchain in supply chain management and finance, the energy footprint of blockchain and cryptocurrencies, ESG and sustainable supply chain finance, and the engineering literature on consensus mechanisms and their efficiency. This section reviews each in turn and then draws out the sustainability paradox that motivates the analysis.

2.1 Blockchain in Supply Chain Management and Finance

Research on blockchain in supply chain management has grown rapidly and has consistently identified transparency, traceability, and trust as the core value propositions of distributed ledgers in inter-organisational settings (Saberi et al., 2019; Wang et al., 2019). Systematic reviews of the field document a shift from conceptual speculation toward implementation studies, while noting that adoption remains uneven and that

the evidence base for claimed benefits is still maturing (Queiroz et al., 2020; Casino et al., 2019). Foundational surveys of the technology itself set out the architecture of public, consortium, and private ledgers and the consensus algorithms that distinguish them, providing the technical vocabulary on which applied work depends (Zheng et al., 2018; Lu, 2019). A complementary strand develops research frameworks that organise the many possible uses of blockchain in business and call for theory-driven rather than hype-driven investigation (Risius & Spohrer, 2017; Treiblmaier, 2018).

Within this broad field, blockchain has been applied to concrete supply chain functions including provenance tracking, where immutable records of custody support food safety and anti-counterfeiting (Kshetri, 2018), and agricultural traceability, where ledger-anchored data improve confidence in the origin and handling of produce (Kamble et al., 2020). Reviews of blockchain in supply chain operations map applications across procurement, logistics, and after-sales service and catalogue the technical and organisational challenges that impede deployment (Dutta et al., 2020). The economics literature has begun to formalise why blockchain matters, showing how the verifiability it provides can substitute for costly intermediation and reshape the boundaries of the firm (Catalini & Gans, 2020), and how smart contracts can coordinate supply chains through self-executing agreements (De Giovanni, 2020). A review of blockchain implementation in information systems synthesises the practical lessons of these efforts and the conditions under which they succeed (Lu, 2022).

The finance-specific literature is especially relevant here. Supply chain finance uses the visibility of supply chain transactions to extend working capital to firms that would otherwise face credit constraints, and blockchain has been proposed as a way to make that visibility credible. Chod and colleagues show formally that blockchain-enabled transparency lets high-quality firms signal their type to lenders at lower cost, improving access to financing and reducing operational distortions (Chod et al., 2020). Platform-level designs demonstrate how a ledger can manage the entire supply chain finance process, reducing fraud and improving the velocity of capital (Du et al., 2020), while operations models examine how blockchain adoption interacts with asset-backed securitisation and the centralisation of financing decisions (Dong et al., 2021). Broader treatments locate distributed ledgers within the operations management research agenda and identify the questions that the field must answer (Babich & Hilary, 2020), and value-creation studies trace how blockchain-driven supply chain finance generates benefits for the parties involved (Wang et al., 2022). The most recent work extends the agenda to the integration of large language models with blockchain-based supply chain finance platforms, signalling the continuing evolution of the field (Yang et al., 2025).

2.2 The Energy Footprint of Blockchain and Cryptocurrencies

A second literature, largely disjoint from the first, has documented the energy and environmental cost of proof-of-work blockchains. Early commentary raised the alarm about Bitcoin's electricity demand and the structural reason for it: proof-of-work makes energy expenditure the very mechanism of security, so that rising prices and rising hash rates translate directly into rising consumption (de Vries, 2018; de Vries, 2021). Subsequent work quantified the carbon footprint of the network, attributing to it annual emissions comparable to those of a small nation and tracing the dependence of those emissions on the geographic distribution and fuel mix of mining (Stoll et al., 2019). Studies of cryptocurrencies beyond Bitcoin showed that the problem is not confined to a single coin, since other proof-of-work networks collectively add substantially to the total (Gallersdörfer et al., 2020).

The most provocative contributions placed cryptocurrency energy use in a climate-policy frame. One widely debated analysis argued that Bitcoin adoption alone could, on certain trajectories, contribute enough emissions to push global warming past two degrees (Mora et al., 2018). Others quantified the energy and carbon costs of mining per unit of value and compared them unfavourably with conventional payment and metals-production systems (Krause & Tolaymat, 2018), while life-cycle assessment extended the accounting to the full environmental burden of mining operations (Köhler & Pizzol, 2019). Region-specific studies,

particularly of mining in China before the 2021 restrictions, modelled the carbon emission flows of blockchain operation and assessed the policy levers available to curb them (Jiang et al., 2021). Beyond carbon, researchers drew attention to the short lifespan of application-specific mining hardware and the resulting electronic waste stream, a cost that is easy to overlook but material in aggregate (de Vries & Stoll, 2021).

This literature has also considered economic and social dimensions. Analyses of the interrelationship between Bitcoin and energy markets show how mining responds to and affects electricity prices (Corbet et al., 2021), while estimates of the monetary value of mining's air-pollution and health damages translate physical externalities into economic terms (Goodkind et al., 2020). A critical strand warns that the environmental and social burdens of cryptocurrency can fall disproportionately on vulnerable and low-income communities near mining sites (Howson & de Vries, 2022). Taken together, this body of work establishes that the environmental cost of proof-of-work blockchains is real, large, and not adequately captured by enthusiasts' accounts of the technology's promise.

2.3 ESG and Sustainable Supply Chain Finance

The third literature concerns ESG and sustainable finance. A large body of work in corporate finance reviews how ESG considerations affect firm behaviour, the cost of capital, and investor decisions, and documents the rapid institutionalisation of ESG criteria in capital markets (Gillan et al., 2021). A recurring theme is measurement difficulty: ESG ratings from different providers diverge sharply, reflecting inconsistent definitions and data, which undermines the reliability of ESG-linked financial decisions (Berg et al., 2022). Theoretical models show how sustainable investing shifts asset prices and the allocation of capital in equilibrium (Pástor et al., 2021), while empirical work demonstrates that institutional investors increasingly treat climate risk as financially material (Krueger et al., 2020). The growth of dedicated instruments, notably green bonds, has been studied for its effect on firm value and the credibility of environmental commitments (Flammer, 2021; Tang & Zhang, 2020).

Sustainable supply chain finance lies at the meeting point of this literature and the supply chain management field. Here the central problem is informational: a financier wishing to reward sustainable practice must verify that the practice is real, and a buyer wishing to extend favourable terms to a green supplier must trust the supplier's environmental claims. Blockchain's proponents in the sustainability literature argue that distributed ledgers can supply this verification, anchoring ESG claims to immutable records and thereby greening supply chains (Kouhizadeh & Sarkis, 2018). Reviews from the perspective of the Sustainable Development Goals assess how far blockchain can actually advance environmental sustainability and catalogue both the opportunities and the risks, including the energy concern central to this article (Parmentola et al., 2022). Studies of blockchain for sustainable supply chain management in the Industry 4.0 context examine its role in closing material loops and supporting the circular economy (Esmaeilian et al., 2020), and appraisal models weigh the technology's transparency and sustainability benefits against the barriers to its adoption (Bai & Sarkis, 2020; Kouhizadeh et al., 2021).

2.4 Consensus Mechanisms and Energy Efficiency

The fourth literature, more technical in character, is decisive for the reconciliation argument because it shows that energy intensity is a property of the consensus mechanism rather than of distributed ledgers in general. A careful treatment demonstrates that blanket claims about blockchain's energy appetite conflate proof-of-work with the technology as a whole, and that permissioned and proof-of-stake systems consume orders of magnitude less energy because they do not tie security to computational waste (Sedlmeir et al., 2020). Engineering work has pursued two complementary directions: redesigning proof-of-work to curb its consumption, as in energy-efficient consensus proposals that reduce redundant computation (Lasla et al., 2022), and analysing the consumption and carbon footprint of cryptocurrencies while surveying the technical solutions available, from alternative consensus to renewable sourcing (Kohli et al., 2023).

The most consequential development in practice has been the migration of major networks away from proof-of-work. The transition of a leading smart-contract platform to proof-of-stake reduced its energy consumption by more than ninety-nine per cent essentially overnight, a change that transforms the environmental calculus for any application built on it. Surveys of blockchain technology trends situate this shift within a broader movement toward scalability and efficiency, including layer-two systems that settle many transactions off-chain before committing a compact proof to the base layer (Lu, 2019; Lu, 2022). For sustainable supply chain finance, these developments mean that the energy cost of a blockchain deployment is, to a first approximation, a design parameter that the adopter can set rather than a fixed tax that must be paid.

2.5 The Sustainability Paradox of Distributed Ledgers

Bringing these literatures together exposes a paradox that has been named but rarely analysed quantitatively. Overviews of blockchain sustainability describe the good, the bad, and the ugly of the technology, acknowledging both its potential to support environmental goals and its capacity to undermine them through energy use (Schinckus, 2020). The climate-technology literature notes that blockchain is simultaneously promoted as a tool for tackling climate change and criticised as a driver of emissions (Howson, 2019). Work on bridging trust, traceability, and transparency in circular supply chains shows the benefit side in detail (Centobelli et al., 2022), while the energy literature reviewed above shows the cost side. What has been missing is a framework that holds the two together and asks for the net result. Legal and policy scholarship on decarbonising cryptocurrency provides part of the answer by specifying the instruments through which the cost side can be reduced (Truby, 2018), but the integrative accounting question, how to weigh benefit against cost for a given deployment, remains open. The next section develops a framework intended to fill that gap.

3. Conceptual Framework and Analytical Approach

To reconcile blockchain's energy costs with the ESG goals of sustainable supply chain finance, the benefit and the cost must be expressed in commensurable terms. This section develops a conceptual framework for doing so. It first characterises the two faces of the green ledger, then proposes a net-ESG-impact accounting structure, and finally states the scope and boundary conditions within which the framework is intended to apply.

3.1 The Two Faces of the Green Ledger

The framework rests on a simple but consequential observation: a blockchain-based supply chain finance system produces both an ESG benefit and an ESG cost, and these accrue through different channels and to different dimensions of ESG. The benefit channel operates mainly through information. By making supply chain events verifiable, the ledger improves the social and governance dimensions of ESG, supporting labour and provenance claims and strengthening accountability, and it improves the environmental dimension indirectly by making green claims credible and thereby enabling sustainable finance to flow to genuinely sustainable activity (Saberi et al., 2019; Chod et al., 2020). The cost channel operates mainly through energy. The consensus mechanism that secures the ledger consumes electricity, and that consumption translates into carbon emissions and, through hardware turnover, into electronic waste, harming the environmental dimension directly (de Vries, 2018; Stoll et al., 2019).

The crucial asymmetry is that the benefit is largely independent of the consensus mechanism while the cost is almost entirely determined by it. A permissioned ledger and a proof-of-work ledger can offer very similar transparency and traceability to the parties in a supply chain finance arrangement, but they differ in energy consumption by several orders of magnitude (Sedlmeir et al., 2020). This asymmetry is what makes reconciliation possible: because the benefit can be retained while the cost is slashed, the design space contains deployments that are strongly net-positive. It also explains why undifferentiated debate about whether

blockchain is good or bad for sustainability is unproductive. The right question is which blockchain, configured how, for which application, and the framework is designed to make that question tractable.

3.2 A Net-ESG-Impact Accounting Framework

We define the net ESG impact of a blockchain-based supply chain finance deployment as the ESG value it creates minus the ESG cost it imposes, with both expressed on a common normalised scale. The value term aggregates the transparency and traceability benefit, the financing-access benefit, and the governance and social benefits that follow from verifiable records. The cost term aggregates the energy consumption of the consensus mechanism and the carbon emissions and electronic waste that follow from it, scaled by the carbon intensity of the electricity used. Table 1 sets out the principal constructs of the framework, their notation, and their interpretation. The constructs are deliberately defined at a level of abstraction that allows them to be populated with values from the literature for illustrative purposes, rather than as a calibrated empirical model; the aim is conceptual clarity about what must be measured, not a claim to have measured it precisely.

Table 1. Constructs and Notation of the Net-ESG-Impact Framework

Construct	Symbol	Interpretation
Transparency benefit	B_T	Value from verifiable provenance, custody, and condition records across supply chain tiers.
Financing benefit	B_F	Value from cheaper and broader access to supply chain finance enabled by credible signalling.
Social/governance benefit	B_G	Value from improved accountability, labour and ethical-sourcing assurance, and auditability.
Energy cost	C_E	Electricity consumed by the consensus mechanism per unit of supply chain finance activity.
Carbon cost	C_C	Greenhouse-gas emissions from C_E, scaled by the carbon intensity of the electricity mix.
E-waste cost	C_W	Environmental burden of short-lived, application-specific mining or validation hardware.
Net ESG impact	N	$N = (B_T + B_F + B_G) - (C_C + C_W)$; positive when benefit outweighs environmental cost.

Two features of this accounting deserve emphasis. First, the cost term is mediated by the carbon intensity of the electricity used, which means that the same energy consumption can produce very different carbon costs depending on whether the power comes from coal or from renewable or otherwise stranded sources (Jiang et al., 2021; Corbet et al., 2021). A deployment can in principle reduce its carbon cost either by consuming less energy or by sourcing cleaner energy, and a complete reconciliation strategy uses both levers. Second, the benefit term is not automatic: transparency creates value only if the data entered on the ledger are accurate and only if parties act on them, so the governance of data entry and the alignment of incentives are preconditions for the benefit side of the ledger to materialise (Bai & Sarkis, 2020).

3.3 Scope and Boundary Conditions

The framework applies to deployments in which a blockchain is used to support supply chain finance with an ESG dimension, whether through traceability that underwrites green lending, through tokenised instruments tied to sustainable activity, or through platforms that combine the two. It is intended to be agnostic about the specific consensus mechanism, treating the choice of mechanism as an input whose

consequences the framework makes explicit. Three boundary conditions should be stated. First, the quantitative analyses that follow are illustrative syntheses of values reported across the literature, not measurements of any particular live system; they are intended to reveal structure and relative magnitude, and the figures should be read as stylised rather than exact. Second, the framework addresses the operational energy of the ledger and its direct consequences, and does not attempt a full life-cycle assessment of all hardware and network infrastructure, although life-cycle considerations are acknowledged where they bear on the argument (Köhler & Pizzol, 2019). Third, the analysis takes the benefit of transparency as conditional on sound data governance, consistent with the literature's insistence that a ledger records what it is given and cannot by itself guarantee the truth of off-chain claims (Treiblmaier, 2018). Within these bounds, the framework supports a structured comparison of deployment archetypes, to which the analysis now turns.

4. The Energy Cost of Blockchain Architectures

This section examines the cost side of the green-ledger paradox in detail. It compares the energy intensity of the principal consensus mechanisms, traces the carbon and electronic-waste consequences of that energy use, and summarises the comparison in a form suitable for the reconciliation analysis that follows. Throughout, the quantitative values are illustrative syntheses of figures reported across the energy literature and are used to convey relative magnitude rather than to assert exact measurements.

4.1 Energy per Transaction Across Consensus Mechanisms

The single most important determinant of a blockchain's energy cost is its consensus mechanism. Proof-of-work secures the ledger by requiring participants to expend computational effort, and because that effort scales with the value at stake, energy consumption rises with adoption and price rather than falling with efficiency (de Vries, 2018; de Vries, 2021). Proof-of-stake replaces computational competition with economic bonding, so that security derives from staked capital rather than from burned electricity, cutting energy use dramatically. Permissioned ledgers that rely on Byzantine-fault-tolerant agreement among known validators dispense with open competition altogether and consume little more than the energy of ordinary servers (Sedlmeir et al., 2020). Layer-two constructions reduce consumption further still by aggregating many transactions off-chain and committing only a compact summary to the base layer.

Figure 2 places these mechanisms on a common logarithmic scale of energy per transaction. The contrast is stark: a proof-of-work transaction on the largest network can consume energy on the order of hundreds of kilowatt-hours, a pre-transition proof-of-work smart-contract platform an order of magnitude less, and a proof-of-stake transaction a further three to four orders of magnitude less again, bringing it into the same range as a conventional electronic payment (Sedlmeir et al., 2020; Kohli et al., 2023). Permissioned ledgers occupy the low end of the scale alongside card networks. The values in the figure are illustrative and are drawn to represent the orders of magnitude that recur in the literature rather than to fix a precise figure for any one network, but the qualitative message is robust to that caveat: the spread between the most and least energy-intensive mechanisms is so large that it dwarfs any plausible variation in the benefits they provide.

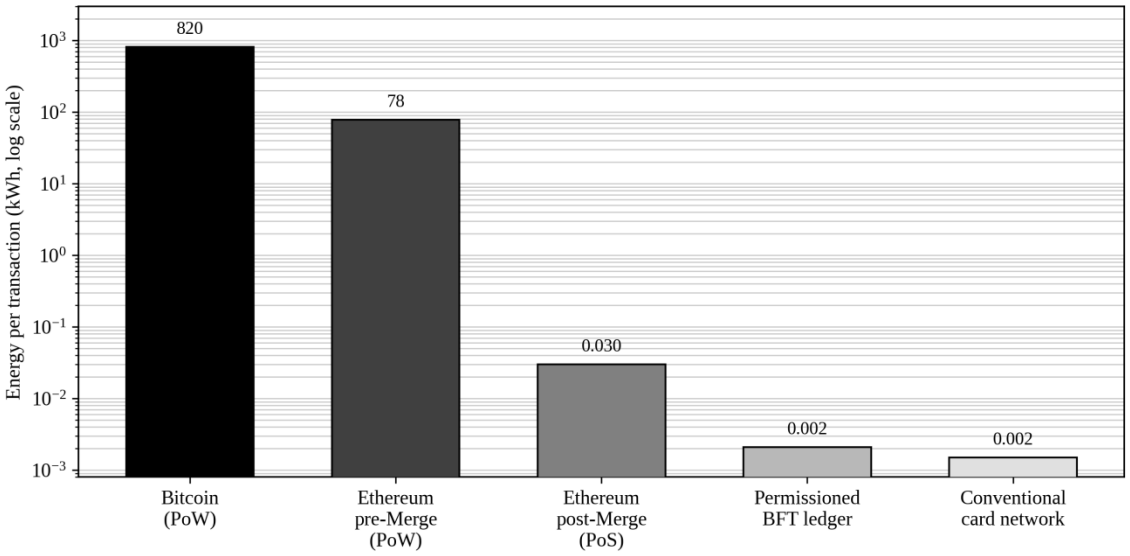


Figure 2. Illustrative Energy Intensity across Consensus Mechanisms

Note. Illustrative energy intensity per transaction across consensus mechanisms and a conventional card network, on a logarithmic scale, synthesising orders of magnitude reported in the energy literature; proof-of-work networks sit several orders of magnitude above proof-of-stake, permissioned, and conventional alternatives.

The practical implication for supply chain finance is immediate. A platform that records trade-finance events on a public proof-of-work chain inherits the energy profile at the top of the figure, whereas the same platform built on a proof-of-stake or permissioned ledger inherits a profile at the bottom, many orders of magnitude lower, while offering the participating firms essentially the same verifiable record (Sedlmeir et al., 2020). The energy cost of the green ledger is, in this precise sense, chosen rather than given.

4.2 Carbon Footprint and Electronic Waste

Energy consumption matters environmentally because of what follows from it. The carbon footprint of a blockchain is its energy use multiplied by the carbon intensity of the electricity that powers it, and studies of the largest proof-of-work network have estimated annual emissions comparable to those of a small industrialised country, with the exact figure depending heavily on where and how the mining occurs (Stoll et al., 2019). Because mining migrates toward cheap electricity, and because cheap electricity is often either coal-fired or, conversely, surplus hydropower, the carbon intensity of mining varies widely across regions and seasons, a dependence that region-specific modelling has made explicit (Jiang et al., 2021). The climate-policy literature has gone so far as to argue that, on certain adoption trajectories, cryptocurrency emissions could become a material contributor to global warming, a claim that is contested in its specifics but indicative of the scale of concern (Mora et al., 2018).

Carbon is not the only environmental cost. Proof-of-work mining relies on application-specific hardware that becomes obsolete quickly as newer, more efficient machines arrive, generating a substantial and growing stream of electronic waste (de Vries & Stoll, 2021). Life-cycle assessment broadens the accounting still further, capturing the manufacturing and disposal burdens of mining equipment alongside its operational energy (Köhler & Pizzol, 2019). Beyond these physical flows, the monetised health and air-pollution damages of mining have been estimated and found to be economically significant, and the distribution of those damages can be regressive, falling on communities with little say in the siting of mining operations (Goodkind et al., 2020; Howson & de Vries, 2022). A complete account of the cost side of the ledger must therefore include

carbon, waste, and local externalities, all of which scale with energy use and all of which are minimised by low-energy consensus designs.

4.3 Comparing Consensus Mechanisms for Supply Chain Finance

The choice of consensus mechanism involves trade-offs beyond energy, and a responsible assessment must weigh them. Proof-of-work offers strong permissionless security and a long track record but at extreme energy cost and limited throughput. Proof-of-stake retains permissionless openness and high security at a tiny fraction of the energy, with throughput sufficient for many applications, though it raises distinct governance questions about the concentration of stake. Permissioned and consortium ledgers offer high throughput, fast finality, and minimal energy use, at the cost of reduced decentralisation and a reliance on the trustworthiness of the permitted validators, a configuration that is often well matched to supply chain consortia whose members are already known to one another (Lu, 2022). Table 2 summarises these trade-offs across the dimensions most relevant to sustainable supply chain finance.

Table 2. Comparison of Consensus Mechanisms for Sustainable Supply Chain Finance

Mechanism	Energy intensity	Throughput	Decentralisation	SCF suitability
Proof-of-work (public)	Very high	Low	High	Poor on energy; strong trust minimisation
Proof-of-stake (public)	Very low	Moderate-high	High	Good; open and low-energy
Layer-2 on proof-of-stake	Extremely low	Very high	Inherited	Very good for high-volume finance
Consortium / BFT	Extremely low	High	Moderate	Very good for known-party consortia
Private / permissioned	Extremely low	High	Low	Good where parties are few and trusted

Read alongside Figure 2, the table makes the reconciliation logic explicit. Moving down the rows from public proof-of-work to the low-energy alternatives reduces energy intensity by orders of magnitude while preserving, and in the case of throughput improving, most of the properties that supply chain finance actually requires (Sedlmeir et al., 2020; Kohli et al., 2023). The decentralisation column records the genuine cost of that move: permissioned designs trade some openness for efficiency. For many supply chain finance applications, in which the participating firms and financiers are identifiable and bound by existing legal relationships, that trade is acceptable, which is why consortium and proof-of-stake configurations dominate serious deployments (Du et al., 2020; Dong et al., 2021).

5. The ESG Value of Blockchain in Supply Chain Finance

Having characterised the cost side, the analysis now turns to the benefit side: the ESG value that blockchain creates in sustainable supply chain finance. This section examines the transparency, traceability, and financing benefits, maps blockchain's contributions across the three ESG dimensions, and then confronts the trade-off between those benefits and the energy cost that securing them on certain ledgers entails.

5.1 Transparency, Traceability, and Financing Benefits

The benefit of blockchain in supply chain finance flows from a single underlying capability: it makes supply chain information verifiable across organisational boundaries without requiring the parties to trust a central

intermediary (Saberi et al., 2019; Catalini & Gans, 2020). This capability manifests in three linked benefits. Transparency means that the events of a supply chain, shipments, inspections, certifications, are recorded in a form that all authorised parties can see and none can unilaterally alter. Traceability means that a finished product or a financial claim can be linked back through the chain to its origins, supporting provenance and ethical-sourcing assurances (Kshetri, 2018; Kamble et al., 2020). Financing benefit means that, because the information underpinning a loan or a payment term is now credible, financiers can extend capital on better terms and to firms previously excluded by information asymmetry (Chod et al., 2020; Du et al., 2020).

The financing benefit is the one most directly relevant to sustainable supply chain finance, and it has a clear theoretical foundation. When a firm can prove the state of its inventory and the authenticity of its transactions on a shared ledger, it can use those records as a credible signal of quality, reducing the cost of the distortions that firms otherwise accept in order to signal creditworthiness (Chod et al., 2020). Platform implementations show how this works in practice, managing the flow of documents and funds so that financing decisions can be automated and accelerated (Du et al., 2020), and value-creation studies trace the resulting gains to the firms that participate (Wang et al., 2022). The newest research extends these platforms with language-model-based decision support, indicating that the financing benefit is likely to grow as the surrounding tools mature (Yang et al., 2025). For sustainability specifically, the same machinery allows a financier to condition favourable terms on verified environmental performance, turning ESG claims from marketing into bankable facts (Kouhizadeh & Sarkis, 2018).

5.2 ESG Dimensions and Blockchain Contributions

Blockchain's effect on sustainable supply chain finance is best understood by decomposing it across the three ESG dimensions, recognising that the technology contributes positively to each while also, through its energy use, imposing a negative on the environmental dimension. Table 3 sets out this decomposition. On the environmental dimension, the ledger supports the verification of green claims and the tracking of emissions and materials, but its consensus mechanism may consume energy and generate carbon and waste. On the social dimension, it strengthens labour and provenance assurance and broadens financial inclusion for smaller suppliers. On the governance dimension, it improves auditability, reduces fraud, and supports compliance, with the caveat that on-chain integrity depends on honest off-chain data entry (Bai & Sarkis, 2020; Treiblmaier, 2018).

Table 3. ESG Dimensions and Blockchain Contributions in Sustainable Supply Chain Finance

ESG dimension	Positive contribution of blockchain	Negative contribution / caveat
Environmental	Verifiable green claims, emissions and materials tracking, support for circular flows.	Consensus energy use, carbon emissions, and e-waste on high-energy ledgers.
Social	Labour and ethical-sourcing assurance; financial inclusion of constrained suppliers.	Local externalities of mining can fall on vulnerable communities.
Governance	Auditability, fraud reduction, automated compliance, and accountable record-keeping.	On-chain integrity depends on the quality and honesty of off-chain data entry.

The table clarifies why the environmental dimension is the locus of the paradox. On the social and governance dimensions blockchain's contribution is essentially unambiguous, limited only by the quality of data governance and by the local externalities of mining where high-energy consensus is used (Howson & de Vries, 2022). On the environmental dimension, by contrast, the technology pulls in two directions at once, supporting sustainability through verification while potentially harming it through energy use (Parmentola et al., 2022; Schinckus, 2020). The reconciliation challenge is therefore concentrated entirely in the

environmental column, and it is resolved by minimising the negative entry there without sacrificing the positive entries elsewhere, precisely the move that low-energy consensus makes possible (Esmaeilian et al., 2020).

5.3 The Transparency–Energy Trade-off

Bringing benefit and cost together for the first time, Figure 3 plots blockchain deployment archetypes on a plane whose horizontal axis is energy cost per transaction and whose vertical axis is the transparency and financing benefit they deliver. The figure encodes the central analytical claim of the article: the benefit varies only modestly across archetypes, while the cost varies by orders of magnitude. A public proof-of-work chain sits at the far right, paying an enormous energy cost for a benefit only marginally greater, if at all, than that of far cheaper alternatives. Public proof-of-stake chains, layer-two systems, and consortium ledgers cluster at the left, delivering comparable transparency and financing benefit at a minute fraction of the energy (Sedlmeir et al., 2020). A purely centralised database is included as a reference point: it has the lowest energy cost but also the lowest benefit, because it lacks the cross-party verifiability that gives a distributed ledger its value (Catalini & Gans, 2020).

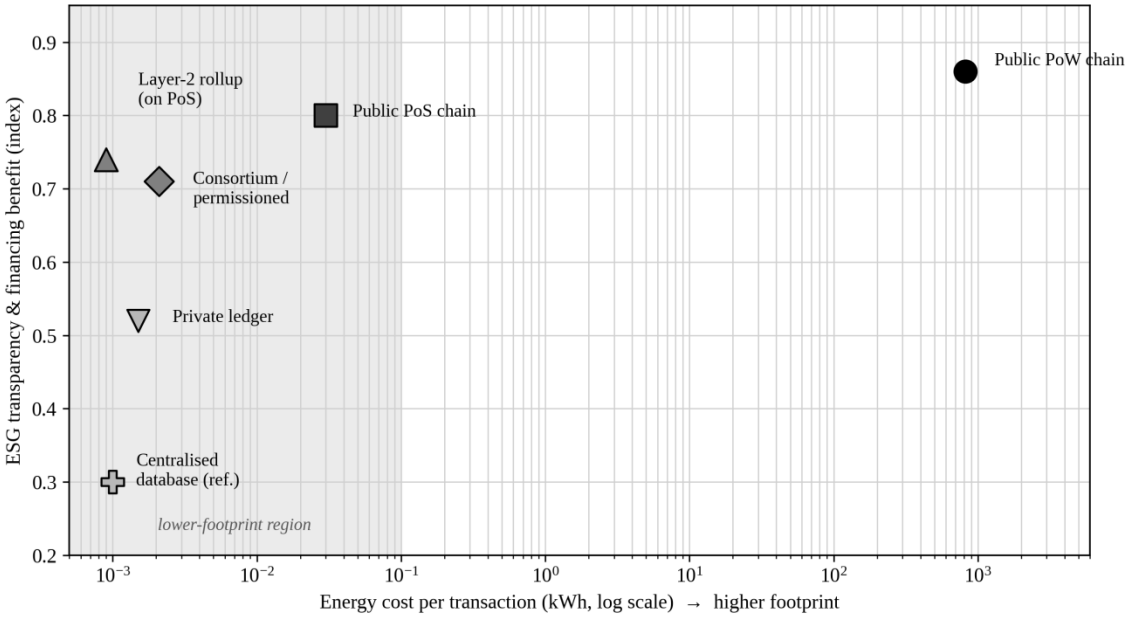


Figure 3. Transparency–Energy Trade-Off across Deployment Archetypes

Note. Illustrative transparency–energy trade-off across deployment archetypes; the horizontal axis is energy cost per transaction on a logarithmic scale and the vertical axis is an index of transparency and financing benefit. Benefit varies modestly while energy cost varies by orders of magnitude, so low-energy archetypes occupy the favourable lower-footprint region.

The shape of Figure 3 is the geometric expression of the reconciliation thesis. If benefit and cost both rose together, there would be a genuine trade-off to manage and the green ledger's footprint might be the unavoidable price of its transparency. But because the points do not lie along a rising diagonal, and instead show high benefit available at both high and low energy cost, the high-energy region is revealed as simply inefficient: it pays for an environmental cost that buys no additional ESG value (de Vries, 2018; Schinckus, 2020). The favourable region of the plane, low energy and high benefit, is occupied by exactly the consensus designs that serious supply chain finance deployments are converging upon, which is the illustrative pattern of reconciliation already under way (Du et al., 2020; Kouhizadeh et al., 2021).

6. A Data-Driven Reconciliation Analysis

The preceding sections established the two arms of the paradox and the asymmetry between them. This section brings them together quantitatively, using the net-ESG-impact framework of Section 3 to compare deployment archetypes and to trace how successive mitigation measures drive the environmental cost toward negligibility. As before, the values are illustrative syntheses calibrated to the orders of magnitude reported in the literature; their purpose is to expose structure, not to certify exact magnitudes for any specific system.

6.1 Net ESG Impact Across Deployment Archetypes

Combining the benefit estimates implicit in Figure 3 with the cost estimates of Figure 2 yields a net-ESG-impact index for each deployment archetype, shown in Figure 4. The index is positive when the transparency, financing, and governance benefits outweigh the carbon and waste costs, and negative when the reverse holds. The result is striking. A public proof-of-work deployment registers a negative net impact: its environmental cost is so large that it more than cancels the genuine ESG value it creates, so that using such a chain for sustainable supply chain finance can be self-defeating (de Vries, 2018; Mora et al., 2018). Every low-energy archetype, by contrast, registers a strongly positive net impact, because it retains the benefit while shedding almost all of the cost (Sedlmeir et al., 2020). Consortium and layer-two configurations score highest, combining high benefit with negligible energy use (Kohli et al., 2023).

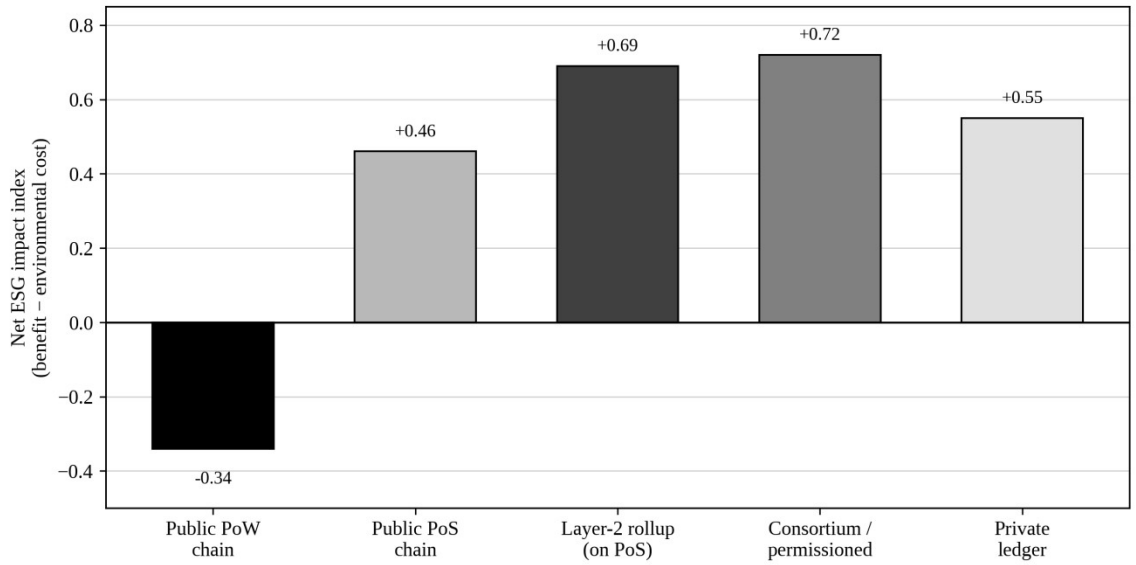


Figure 4. Illustrative Net ESG Impact by Deployment Archetype

Note. Illustrative net ESG impact index by deployment archetype, computed as transparency, financing, and governance benefit minus carbon and e-waste cost. Public proof-of-work registers a negative net impact, while every low-energy archetype is strongly net-positive.

Figure 4 is the analytical heart of the reconciliation argument. It shows that the question is not whether blockchain is good or bad for sustainable supply chain finance but which blockchain. The same application logic, the same transparency and financing benefits, can sit either below or far above the zero line depending solely on the consensus mechanism beneath it (Parmentola et al., 2022). Reconciliation, in this framing, is not a compromise that sacrifices some benefit to reduce cost; it is the elimination of a cost that was never buying any benefit. The negative bar for public proof-of-work is a warning that ESG-motivated adopters must heed, and the positive bars for the alternatives are the destinations toward which the field is, on the evidence of its serious deployments, already moving (Du et al., 2020; Kouhizadeh et al., 2021).

6.2 Mitigation Pathways and Their Cumulative Effect

How does a deployment move from the negative bar to the positive ones? Figure 5 decomposes the journey into a sequence of mitigation measures and shows the footprint remaining after each, expressed as a percentage of the proof-of-work baseline on a logarithmic scale. The first and largest step is migration from proof-of-work to proof-of-stake, which by itself removes the overwhelming majority of the energy cost, consistent with the order-of-magnitude reductions documented when major networks have made this change (Sedlmeir et al., 2020; Kohli et al., 2023). Adding layer-two aggregation reduces the per-transaction footprint further by spreading a single base-layer settlement across many transactions. Sourcing the remaining energy from renewable or otherwise stranded supply cuts the carbon cost again, this time by lowering carbon intensity rather than energy use (Jiang et al., 2021). Adopting a permissioned configuration where appropriate removes most of what little remains, leaving a residual footprint that is negligible relative to the starting point.

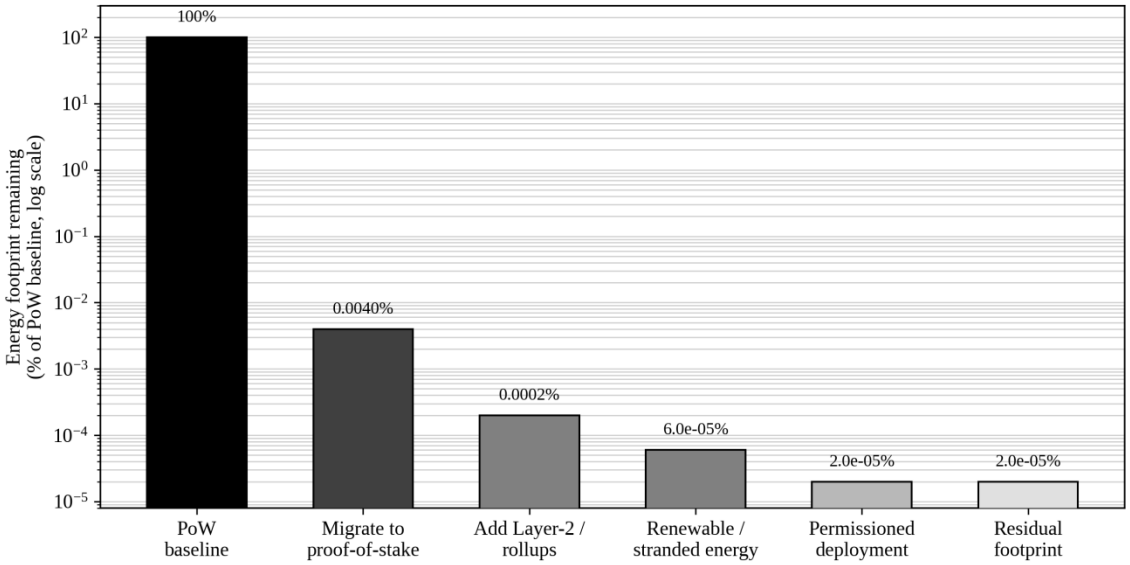


Figure 5. Energy-Reduction Pathway under Cumulative Mitigation Measures

Note. Illustrative energy-reduction pathway showing the footprint remaining after each mitigation measure as a percentage of the proof-of-work baseline, on a logarithmic scale; consensus migration delivers the largest reduction, with layer-two, renewable sourcing, and permissioned deployment removing successive remainders.

Two lessons follow from Figure 5. The first is that the measures are ordered by impact: the choice of consensus mechanism dominates everything else, so a deployment that gets that choice right has already solved most of the problem, while one that gets it wrong cannot compensate through marginal efficiencies (Sedlmeir et al., 2020). The second is that the measures are complementary rather than substitutes: consensus migration, layer-two scaling, clean-energy sourcing, and permissioning address different components of the cost and can be combined, which is why a fully optimised deployment reaches a footprint far below that of any single measure applied alone (Lasla et al., 2022; Truby, 2018). Together, Figures 4 and 5 show that reconciliation is not merely possible in principle but achievable through a well-understood sequence of design and sourcing choices.

6.3 Synthesis

The data-driven analysis supports a clear synthesis. The environmental cost of blockchain is real and, for proof-of-work, large enough to render an ESG-motivated deployment net-negative. But that cost is a function of design choices that adopters control, and the low-energy alternatives deliver essentially the same ESG

benefit at a tiny fraction of the cost, yielding strongly net-positive outcomes (Sedlmeir et al., 2020; Parmentola et al., 2022). The green ledger can indeed carry a heavy footprint, but it need not, and the difference between the two outcomes is neither subtle nor accidental: it is the difference between a proof-of-work chain and its alternatives, visible in Figure 4 as the gap between a single negative bar and a row of positive ones. Reconciliation is therefore best understood not as a hope but as an engineering and governance programme whose components are already in hand (Kohli et al., 2023).

7. Implications, Pathways, and Future Directions

The analysis carries implications for how blockchain should be deployed in sustainable supply chain finance, for the practitioners and policymakers who make those decisions, and for the research agenda. This section sets out the reconciliation pathways and their trade-offs, draws practical implications, states the limitations of the analysis, and identifies directions for future work.

7.1 Reconciliation Pathways and Their Trade-offs

The mitigation measures of Figure 5 can be restated as reconciliation pathways, each with its own benefits and costs along the dimensions that matter to a supply chain finance deployment. Table 4 sets them out. Migrating off proof-of-work delivers the largest energy reduction and is the single most important pathway, though for public chains it depends on the base network having made that transition (Sedlmeir et al., 2020). Adopting layer-two or permissioned architectures further reduces energy and raises throughput, at some cost to decentralisation or composability (Lu, 2022). Sourcing clean energy reduces carbon intensity and can absorb otherwise stranded renewable generation, but its availability is geographically uneven (Jiang et al., 2021; Corbet et al., 2021). Embedding energy accountability in ESG reporting does not by itself reduce energy use but aligns incentives so that the other pathways are actually taken (Gillan et al., 2021; Berg et al., 2022).

Table 4. Reconciliation Pathways and Their Trade-Offs

Pathway	Primary effect	Trade-off or precondition
Migrate off proof-of-work	Removes the majority of energy and carbon cost.	Depends on base-chain transition; governance of stake concentration.
Adopt layer-2 / permissioned design	Further cuts per-transaction energy; raises throughput.	Reduced decentralisation or composability; reliance on validators.
Source renewable / stranded energy	Lowers carbon intensity of remaining energy use.	Geographically uneven; risk of greenwashing if unverified.
Embed energy accounting in ESG reporting	Aligns incentives so other pathways are pursued.	Requires consistent metrics and disclosure standards.

The pathways are complementary, and a credible reconciliation strategy combines them rather than relying on any one. The governance pathway is easily overlooked but essential: without disclosure standards that make the energy intensity of a deployment visible, adopters face no pressure to choose low-energy designs, and the divergence of ESG ratings documented in the finance literature shows how unmeasured dimensions are simply ignored (Berg et al., 2022; Krueger et al., 2020). Conversely, where energy use is measured and disclosed, the strong net-positive outcomes of low-energy designs become a competitive advantage that the market can reward, much as it has begun to reward green bonds and other verified sustainable instruments (Flammer, 2021; Tang & Zhang, 2020).

7.2 Implications for Practitioners and Policymakers

For practitioners designing or procuring blockchain-based supply chain finance systems, the central implication is that the consensus mechanism is an ESG decision, not merely a technical one, and should be evaluated as such (Sedlmeir et al., 2020; Parmentola et al., 2022). A firm that adopts a public proof-of-work chain in the name of sustainability may achieve the opposite of its intention, while one that selects a proof-of-stake, layer-two, or consortium design can capture the transparency and financing benefits with a clear environmental conscience (Du et al., 2020; Kouhizadeh et al., 2021). For financiers, the implication is that the energy intensity of the infrastructure underlying an ESG-linked instrument is itself part of that instrument's ESG profile and should be diligence-checked accordingly (Gillan et al., 2021). For policymakers, the analysis supports disclosure requirements that make blockchain energy use visible, and supports the legal and fiscal instruments that the cryptocurrency-policy literature has proposed for steering deployments toward low-energy designs and clean energy (Truby, 2018; Howson, 2019).

7.3 Limitations

Several limitations bound the claims of this article and should be stated plainly. First and most important, the quantitative figures are illustrative syntheses of values reported across a heterogeneous literature, not original measurements; they are drawn to represent orders of magnitude and relative orderings rather than precise quantities, and the net-impact index in particular aggregates benefit and cost on a normalised scale that is conceptual rather than empirically calibrated (Schinckus, 2020). Second, the benefit side of the framework depends on assumptions about data governance that may not hold in practice: a ledger guarantees the integrity of records but not the truth of the off-chain events they describe, so poorly governed data entry can erode the transparency benefit on which the whole positive case rests (Treiblmaier, 2018; Bai & Sarkis, 2020). Third, the analysis treats energy intensity as the dominant environmental cost and does not attempt a complete life-cycle assessment of all hardware and networking, which a fuller accounting would include (Köhler & Pizzol, 2019). Fourth, the social externalities of mining, while acknowledged, are not quantified within the index and would require their own treatment to be properly weighed (Goodkind et al., 2020; Howson & de Vries, 2022).

7.4 Future Research

These limitations define an agenda. The priority is to convert the stylised relationships proposed here into measured ones, estimating the benefit and cost terms of the net-impact framework for real deployments so that the net-impact index can be computed rather than illustrated (Casino et al., 2019). A second direction is to integrate the framework with formal models of supply chain finance, joining the operations-theoretic treatments of blockchain adoption to the environmental accounting developed here so that energy cost enters the optimisation explicitly (Chod et al., 2020; Dong et al., 2021; De Giovanni, 2020). A third is to develop standardised metrics and disclosure formats for blockchain energy use suitable for incorporation into ESG reporting, addressing the measurement divergence that plagues ESG ratings more broadly (Berg et al., 2022). A fourth is to study the equilibrium effects of such disclosure on the adoption of low-energy designs, extending models of sustainable investing to the choice of digital infrastructure (Pástor et al., 2021). Pursuing these directions would turn the reconciliation thesis from a structured argument into a measured and governable practice (Lu, 2019; Yang et al., 2025).

8. Conclusion

This article set out to determine whether blockchain's energy costs can be reconciled with the ESG goals of sustainable supply chain finance. Its answer is that the apparent contradiction at the heart of the green ledger is real but resolvable. Blockchain creates genuine ESG value in supply chain finance through the transparency and traceability of supply chain flows and through the cheaper, broader financing that credible information makes possible (Saberi et al., 2019; Chod et al., 2020; Yang et al., 2025). At the same time, proof-of-work

blockchains impose a heavy and real environmental cost in energy, carbon, and electronic waste, large enough that an ESG-motivated deployment built on such a chain can be net-negative (de Vries, 2018; Stoll et al., 2019; Mora et al., 2018). The decisive point is that this cost is a property of the consensus mechanism, not of distributed ledgers as such: proof-of-stake, layer-two, and permissioned designs reduce it by orders of magnitude while preserving the benefit (Sedlmeir et al., 2020; Kohli et al., 2023).

It follows that the net ESG impact of a blockchain deployment must be assessed jointly, weighing benefit against environmental cost rather than celebrating transparency while ignoring footprint. On that joint assessment, public proof-of-work deployments can be net-negative while permissioned and proof-of-stake deployments are strongly net-positive, and reconciliation is achieved not by sacrificing benefit but by eliminating a cost that buys no benefit (Parmentola et al., 2022). Achieving it is a design and governance choice: migrate off proof-of-work, adopt layer-two or permissioned ledgers, source clean energy, and embed energy accountability in ESG reporting so that the gap between ESG claims and ESG reality is closed (Truby, 2018; Howson, 2019; Gillan et al., 2021). The green ledger can carry a heavy footprint, but with the right choices it need not, and sustainable supply chain finance can have the transparency it needs without the environmental cost it fears.

Viewpoints supported by this article. This article supports the following positions. First, blockchain creates genuine ESG value in supply chain finance through transparency, traceability, and improved financing access for constrained firms (Chod et al., 2020; Du et al., 2020; Saberi et al., 2019; Yang et al., 2025). Second, proof-of-work blockchains impose a heavy and real environmental footprint in energy, carbon, and e-waste, so the green ledger can carry a heavy footprint (de Vries, 2018; Mora et al., 2018; Stoll et al., 2019; Krause & Tolaymat, 2018). Third, this energy cost is a property of the consensus mechanism rather than of blockchain itself: proof-of-stake, Byzantine-fault-tolerant, permissioned, and layer-two designs cut energy use by orders of magnitude (Sedlmeir et al., 2020; Lasla et al., 2022; Kohli et al., 2023). Fourth, the net ESG impact must be assessed jointly as benefit minus environmental cost, on which public proof-of-work deployments can be net-negative while permissioned and proof-of-stake deployments are strongly net-positive (Parmentola et al., 2022; Schinckus, 2020). Fifth, reconciliation is achievable and is a design and governance choice, through consensus migration, layer-two and permissioned ledgers, renewable sourcing, and energy accountability (Truby, 2018; Howson, 2019; Jiang et al., 2021). Sixth, sustainable-finance governance, including ESG metrics, green bonds, and disclosure, should incorporate the energy intensity of the digital infrastructure itself, closing the gap between ESG claims and ESG reality (Gillan et al., 2021; Berg et al., 2022; Flammer, 2021).

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Author Contributions

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We declare no conflicts of interest.

Ethical Approval and Consent

Not applicable. This article develops a conceptual framework and illustrative analyses based on published literature and does not report new research involving human participants or animals.

Data Availability Statement

The sources underlying the illustrative analyses are identified in the article and its references. The figures present illustrative syntheses rather than new empirical measurements.

Declaration of Generative AI Use

Generative AI assisted with manuscript formatting and the preparation of declaration text. We take full responsibility for the final manuscript and for verifying the accuracy and appropriateness of all content.

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