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Mohamed Rafik Noor Mohamed Qureshi,  
King Khalid University, Saudi Arabia

## \*CORRESPONDENCE

Lukas Stopfer,  
✉ lukas.stopfer@foresteng.uni-freiburg.de

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# Sustainability assessment of blockchain systems in timber supply chains: environmental and economic impacts

Lukas Stopfer<sup>1\*</sup>, Eugen Buss<sup>2</sup>, Alexander Kaulen<sup>3</sup>,  
Ferréol Berendt<sup>4</sup>, Felipe De Miguel<sup>1</sup>, Marcel Püls<sup>5</sup>, Stefan Lier<sup>2</sup>,  
Mirella Elias<sup>6</sup>, Stelian Alexandru Borz<sup>6</sup>, Marc Hanewinkel<sup>7</sup> and  
Thomas Purfürst<sup>8</sup>

<sup>1</sup>Chair of Forest Operations, University of Freiburg, Freiburg, Germany, <sup>2</sup>Department of Logistics and Supply Chain Management, South Westphalia University of Applied Sciences, Meschede, Germany, <sup>3</sup>Department of Timber Logistics and Data Management, German Centre for Forest Work and Technology (KWF), GroßUmstadt, Germany, <sup>4</sup>Department Forest-Wood-Environment, Eberswalde University for Sustainable Development, Eberswalde, Germany, <sup>5</sup>Conservation Department, Government of Swabia, Augsburg, Germany, <sup>6</sup>Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Transilvania University of Braşov, Braşov, Romania, <sup>7</sup>Chair of Forestry Economics and Forest Planning, University of Freiburg, Freiburg, Germany, <sup>8</sup>Chair of Digitized Forestry Processes and Systems, Dresden University of Technology, Dresden, Germany

This study quantifies the energy use, carbon dioxide equivalent (CO<sub>2</sub>e) emissions, and transaction-related costs of distributed ledger technologies (DLTs) in the context of timber traceability. It combines: (i) a PRISMA-guided systematic review of empirical studies on DLT energy consumption; and (ii) benchmark values derived from continuously updated online monitoring sources, captured at defined access dates and fully documented in the . Comparable metrics are reported at the level of individual traceability events (kWh/tx, gCO<sub>2</sub>e/tx, and USD/tx) and are related to a realistic timber supply chain transaction model that was empirically validated in a pilot study. The results reveal substantial differences in sustainability performance across consensus mechanisms. Proof-of-Work (PoW) networks exhibit prohibitively high energy demand and CO<sub>2</sub>e emissions for frequent traceability notarizations. In contrast, Proof-of-Stake (PoS), PBFT-based, hybrid, and Directed Acyclic Graph (DAG) architectures enable low-energy and low-cost event logging. This study bridges the gap between established DLT sustainability research and the operational requirements of regulated forestry traceability by providing a transparent and reproducible benchmarking workflow that includes URLs, access dates and calculation spreadsheets.

## KEYWORDS

consensus, distributed ledger technology, energy consumption, logistics, traceability, forest operation

## 1 Introduction

Deforestation and illegal timber harvesting constitute major global sustainability challenges and are among the key drivers of environmental degradation and biodiversity loss. In response, governments and international organizations have introduced increasingly stringent regulatory frameworks to promote legal and

sustainable timber trade. A prominent example is the European Union Regulation on Deforestation and Forest Degradation (EUDR), which mandates full traceability of timber products placed on the EU market across the entire supply chain [Köthke et al., 2023; Supplementary Material (Stopfer and Buss 2025)]. The EUDR seeks to address structural weaknesses in global forest governance by strengthening transparency, accountability, and sustainable forest management practices.

However, conventional timber tracking systems, including paper-based records, barcodes, QR codes, RFID tags, and satellite monitoring, are increasingly viewed as inadequate due to their susceptibility to tampering, forgery, data loss, and high operational costs (Kaulen et al., 2024). Even well-established certification programs such as the *Forest Stewardship Council (FSC)* and the *Programme for the Endorsement of Forest Certification (PEFC)* rely on centralized databases and manual audits. This reliance introduces inefficiencies and creates opportunities for fraud and corruption. In this context, Distributed Ledger Technologies (DLT), particularly blockchain are gaining attention as robust tools for improving transparency, security, and efficiency in timber traceability. Empirical studies have demonstrated that blockchain technology can facilitate the secure and verifiable storage of supply chain data, helping to reduce illegal logging and strengthen oversight (Düdder and Ross, 2017). The FSC reports that the adoption of blockchain technologies in forestry is accelerating in response to emerging legal traceability requirements. Moreover, when integrated with Internet of Things (IoT) sensors and automated tracking systems, blockchain has the potential to enable near real-time monitoring of wood origin, transport routes, and product quality (Worm and Marus, 2020).

Despite these advantages, concerns persist regarding the environmental implications of blockchain technology. *Proof-of-Work (PoW)* consensus mechanisms, widely employed in cryptocurrencies such as Bitcoin, are highly energy-intensive and contribute substantially to carbon emissions (Kohli et al., 2023; Sarkodie et al., 2023). In contrast, more recent models, including *Proof-of-Stake (PoS)*, hybrid blockchains, and off-chain solutions, offer significantly more energy-efficient alternatives that are more closely aligned with sustainability objectives. From an economic perspective, blockchain has the potential to streamline compliance, reduce fraud, and lower administrative costs. Nevertheless, high implementation costs and technical complexity remain significant barriers, particularly for small and medium-sized enterprises (SMEs) in the forestry sector. This study investigates the potential of blockchain technologies to support the sustainable transformation of timber supply chains. It addresses both ecological and economic dimensions by analyzing peer-reviewed literature and real-world use cases, with the goal of identifying practical and scalable solutions for a secure and sustainable timber industry.

The following research questions (RQs) have been formulated to guide this investigation. It is hypothesized that energy-efficient consensus mechanisms can achieve sustainability without compromising economic feasibility:

- RQ1: What is the energy consumption of DLT-based systems in timber supply chains, and how does the underlying consensus mechanism influence this?
- RQ2: What is the relationship between the energy consumption of DLT systems and their associated CO<sub>2</sub> emissions, and how does this relationship vary across different consensus mechanisms?
- RQ3: What are the financial implications of using DLT-based tracking systems for transactions and coordination in timber supply chains?
- RQ4: Which consensus mechanisms and DLT architectures are most suitable for sustainable implementation in timber supply chains, considering ecological and economic criteria?
- RQ5: How does integrating continuously updated, non-academic data sources affect the accuracy and reliability of energy and emission estimates for DLT systems compared with relying solely on peer-reviewed literature?

These research questions form the conceptual foundation of the study and directly inform its methodological design, which combines a systematic literature review together with the analysis of continuously updated data sources, ensuring both scientific rigor and real-world relevance.

## 2 Materials and methods

The methodological framework of this study is based on two complementary pillars:

1. A systematic literature review conducted to establish the scientific context and identify existing empirical evidence on the energy consumption of distributed ledger technologies (DLT)
2. Data drawn from sources that were updated daily as of 2 February 2025, which were subsequently aggregated and averaged.

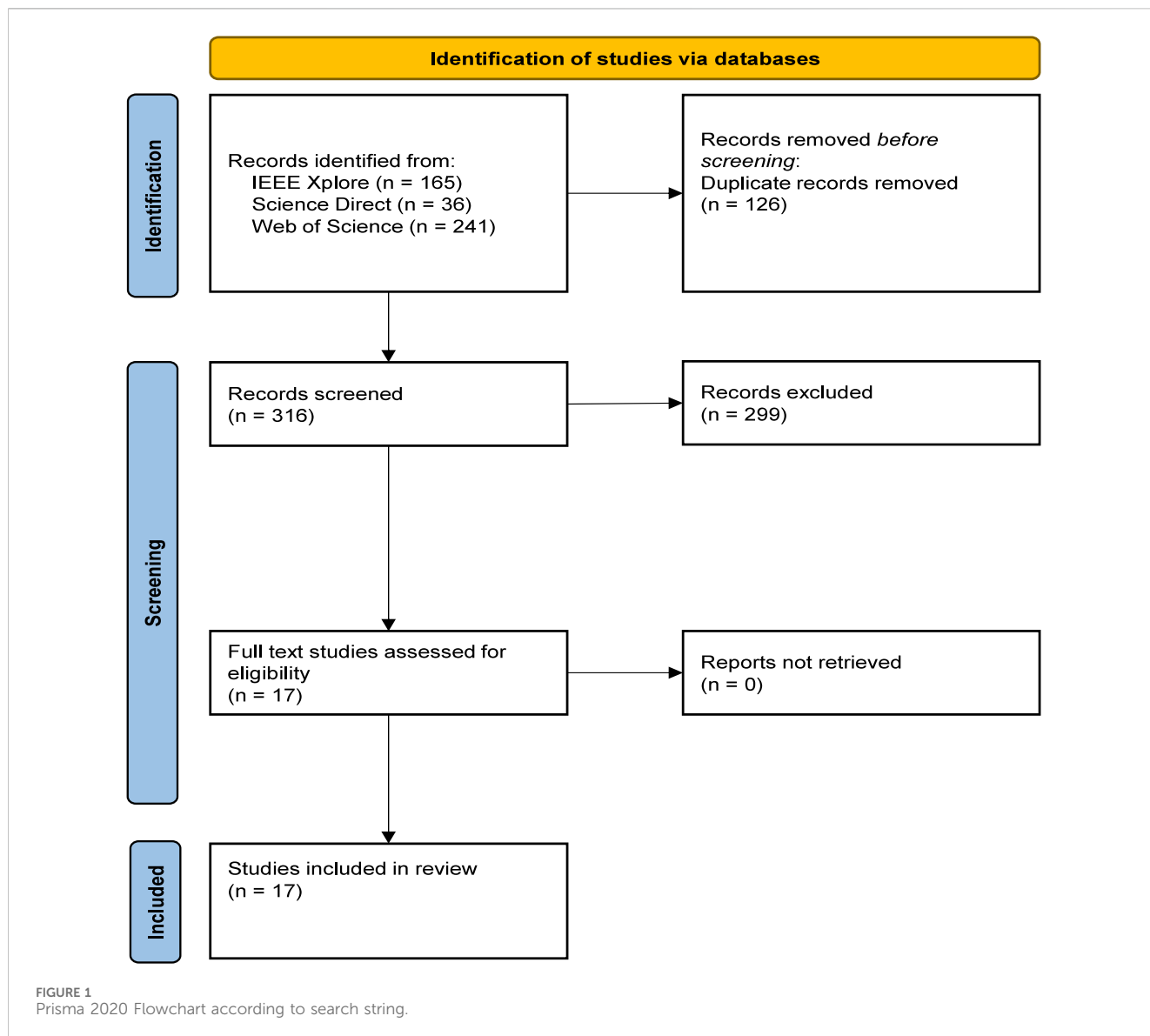
This dual approach provides both a comprehensive theoretical foundation and an empirical representation of the current state of Distributed Ledger Technology (DLT) in terms of energy consumption, carbon emissions, and system efficiency. This combined approach was chosen to balance methodological rigor with empirical relevance in a rapidly evolving technological domain, where the need for innovation is high and new solutions are constantly being developed.

### 2.1 Systematic literature review

The systematic literature review is in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Figure 1), as well as the methodological framework proposed by Okoli and Schabram (2010).

The following three major scientific databases were used to perform the literature search: IEEE Xplore, ScienceDirect and Web of Science. The following search string was applied to ensure the inclusion of the most relevant and high-quality publications:

(DLT OR “Distributed Ledger” OR Blockchain) AND Energy Consumption AND Consensus



The literature search covered the period from 2018 onwards, coinciding with significant modifications to DLT consensus mechanisms. Most notably, this period included Ethereum’s transition from Proof-of-Work (PoW) to Proof-of-Stake (PoS), a shift that substantially improved energy efficiency. Although no language restrictions were applied, most of the identified studies were published in English, and a smaller number in German and Spanish.

The screening process consisted of three stages:

1. Duplicate removal
2. Relevance assessment based on titles and abstracts
3. Full-text review

Studies providing quantitative or empirical data on DLT energy consumption or environmental impact were included. Purely conceptual or theoretical studies, as well as those lacking measurable data, were excluded. This systematic approach

ensured the inclusion of studies offering verifiable, data-driven insights into the sustainability of DLT systems.

Data selection and screening process

In total, 422 publications were initially identified across the three databases. After removing 126 duplicates, 316 unique records remained for screening. Title and abstract screening, followed by full-text assessment, resulted in 17 studies that met all predefined inclusion criteria and were retained for the systematic review.

The main reasons for exclusion were:

- Absence of quantitative data on energy consumption or emissions
- Exclusive focus on consensus design without energy-related analysis
- Reliance on high-level, speculative, or unverifiable estimates
- Analyses of energy consumption unrelated to distributed ledger technologies

TABLE 1 Overview and assessment of PRISMA-Selected studies on DLT consensus mechanisms and energy consumption.

| No. | Authors                 | Short reference   | Publication type          | Main focus  | Quantitative energy data | Qualitative energy assessment            | Relevance category             |
|-----|-------------------------|---|---------------------------|---|--------------------------|--|--------------------------------|
| 1   | Masood et al.           | <i>Consensus algorithms in DLT for open environment</i>             | Journal article           | Comparison of PoW, PoS, PBFT in open environments       | Partial                  | Yes – discusses energy efficiency trends | Conceptual + partial empirical |
| 2   | Lamriji et al.          | <i>Comparative study of consensus algorithms</i>                    | Journal article           | Performance, scalability, security comparison           | No                       | Yes – qualitative energy implications    | Conceptual survey              |
| 3   | Rajan et al.            | <i>Blockchain framework for big data at the edge</i>                | Journal article           | Energy-aware blockchain design for edge computing       | Partial                  | Yes                                      | Application-oriented           |
| 4   | Platt et al.            | <i>Energy footprint beyond PoW</i>                                  | Journal article           | Empirical comparison of PoW, PoS, PBFT, DAG             | Yes                      | Yes                                      | Core quantitative              |
| 5   | Kohli et al.            | <i>Energy consumption and carbon footprints of cryptocurrencies</i> | Journal article           | Energy & CO <sub>2</sub> footprint of major blockchains | Yes                      | Yes                                      | Core quantitative              |
| 6   | Sarkodie et al.         | <i>Assessment of bitcoin carbon footprint</i>                       | Journal article           | Empirical bitcoin mining energy and emissions           | Yes                      | Yes                                      | Core quantitative              |
| 7   | Zhang et al.            | <i>QPBFT consensus algorithm</i>                                    | Journal article           | PBFT variant improving efficiency and latency           | No                       | Yes – energy reduction discussed         | Algorithmic                    |
| 8   | Sealey et al.           | <i>IOTA Tangle 2.0</i>  | Journal article           | DAG consensus for scalable IoT                          | Partial                  | Yes                                      | Emerging DLT                   |
| 9   | Kably et al.            | <i>Lightweight DAG blockchain for IoT</i>                           | Journal article           | Low-power DAG consensus for constrained devices         | Partial                  | Yes                                      | Application-oriented           |
| 10  | Bachani & Bhattachariya | <i>Preferential DPoS (PDPoS)</i>                                    | Journal article           | Modified DPoS for scalability                           | No                       | Yes – efficiency arguments               | Algorithmic                    |
| 11  | Nguyen et al.           | <i>PoS consensus mechanisms for future networks</i>                 | Survey article            | Comprehensive PoS survey                                | No                       | Yes – energy efficiency narrative        | Conceptual survey              |
| 12  | Sasikumar et al.        | <i>Secure big data storage via blockchain</i>                       | Journal article           | Energy-aware consensus for storage systems              | Partial                  | Yes                                      | Application-oriented           |
| 13  | Sedmeir et al.          | <i>Energy consumption of blockchain technology</i>                  | Journal article           | Methodology for measuring blockchain energy use         | Yes                      | Yes                                      | Methodological core            |
| 14  | Saprah & Shaikh         | <i>Impact of bitcoin mining on energy use</i>                       | Journal article           | Drivers of bitcoin energy consumption                   | Yes                      | Yes                                      | Core quantitative              |
| 15  | Bada et al.             | <i>Towards a green blockchain</i>                                   | Review article            | Overview of energy-efficient consensus                  | No                       | Yes                                      | Conceptual review              |
| 16  | Roma & Anwar            | <i>Energy consumption of XRP validator</i>                          | Technical report/ Journal | Empirical XRP validator energy measurement              | Yes                      | Yes                                      | Core quantitative              |
| 17  | Bouraga                 | <i>Taxonomy of blockchain consensus protocols</i>                   | Survey article            | Classification of consensus mechanisms                  | No                       | Yes – efficiency traits                  | Conceptual taxonomy            |

In addition, several measurement-oriented studies were identified via backward and forward citation searching and included strengthening the empirical basis. A complete list of the 17 PRISMA-selected studies, including publication type, scope, and whether quantitative or qualitative energy evidence is provided, is reported in Table 1 to ensure transparency and reproducibility.

Figure 1 summarizes the selection process in accordance with PRISMA 2020.

Despite rigorous screening, the limited number of eligible studies highlights a gap in peer-reviewed research providing empirically grounded and up-to-date measurements of DLT energy use (n = 17). Consequently, the systematic review was

**TABLE 2** Overview of external (non-academic) data sources used for energy, emissions, transactions, and cost metrics of DLT systems (Stopfer and Buss, 2025).

| No. | Data source                           | URL   | Access date   | Description/Data provided  |
|-----|---------------------------------------|---|---------------|--|
| 1   | Carbon ratings index (CCRI)           | <a href="https://indices.carbon-ratings.com/">https://indices.carbon-ratings.com/</a> | 9-February-25 | Annual network energy consumption (kWh/a) and total CO <sub>2</sub> e emissions for major blockchain networks          |
| 2   | Electricity maps ApS                  | <a href="https://www.electricitymaps.com/">https://www.electricitymaps.com/</a>       | 9-February-25 | Country-level electricity mix and CO <sub>2</sub> e intensity (gCO <sub>2</sub> e/kWh) used for emissions calculations |
| 3   | Our world in data (Oxford University) | <a href="https://ourworldindata.org/">https://ourworldindata.org/</a>                 | 9-February-25 | National CO <sub>2</sub> emission factors and energy mix statistics  |
| 4   | Etherscan                             | <a href="https://etherscan.io/">https://etherscan.io/</a>                             | 9-February-25 | Ethereum transaction counts and network activity   |
| 5   | Solscan                               | <a href="https://solscan.io/">https://solscan.io/</a>                                 | 9-February-25 | Solana transaction volume and network statistics   |
| 6   | XRPScan                               | <a href="https://xrpscan.com/">https://xrpscan.com/</a>                               | 9-February-25 | Ripple (XRP Ledger) transaction counts and validator metrics   |
| 7   | IOTA explorer                         | <a href="https://explorer.iota.org/">https://explorer.iota.org/</a>                   | 9-February-25 | IOTA network activity and transaction volume   |
| 8   | BitInfoCharts                         | <a href="https://bitinfocharts.com/">https://bitinfocharts.com/</a>                   | 9-February-25 | Bitcoin and Ethereum transaction fees, transaction counts  |
| 9   | YCharts                               | <a href="https://ycharts.com/">https://ycharts.com/</a>                               | 9-February-25 | Average transaction fees for Bitcoin and Ethereum  |
| 10  | The block (data)                      | <a href="https://www.theblock.co/data">https://www.theblock.co/data</a>               | 9-February-25 | Comparative on-chain metrics (BTC, ETH, SOL)   |
| 11  | CoinCodex                             | <a href="https://coincodex.com/">https://coincodex.com/</a>                           | 9-February-25 | Gas fees, transaction costs, price-based conversions   |
| 12  | Coinbase                              | <a href="https://www.coinbase.com/">https://www.coinbase.com/</a>                     | 9-February-25 | Cryptocurrency price data (USD conversions)  |
| 13  | GasFees.org                           | <a href="https://gasfees.org/">https://gasfees.org/</a>                               | 9-February-25 | Transaction fee estimates for PoS networks (e.g., Cardano)   |
| 14  | IOTA services                         | <a href="https://www.iota-services.com/">https://www.iota-services.com/</a>           | 9-February-25 | Zero-fee and DAG architecture documentation  |

complemented by continuously updated monitoring sources to generate current benchmark values, with all URLs, access dates, and calculation steps documented in the Supplementary Material (Stopfer and Buss, 2025).

The systematic literature review was complemented by continuously updated, non-academic data sources, including university-affiliated research portals, non-governmental organizations (NGOs), and publicly accessible monitoring platforms. Although these sources do not always meet traditional peer-review standards, their near-time updates and methodological transparency make them indispensable for accurately reflecting the current operational state of DLT networks. The integration of these sources allows this study to balance scientific rigor with empirical relevance and to derive representative benchmark values for energy consumption and emissions in practice.

## 2.2 Use of continuously updated data sources

Given the dynamic and rapidly evolving nature of DLTs and their associated energy demands, peer-reviewed academic literature alone is insufficient to fully capture real-time developments in this domain. The present study complements the systematic literature review with continuously updated online data sources (Table 2).

Where available, data was retrieved from university research portals, non-governmental organizations (NGOs), and publicly accessible monitoring platforms providing regularly updated metrics on distributed ledger technology (DLT) performance.

These sources report key operational indicators for large blockchain systems, including network-level power consumption, estimated CO<sub>2</sub> emissions, transaction volumes, throughput, and transaction fees. All external data was collected manually from the respective online sources at explicitly documented times to ensure traceability and temporal consistency. As different data providers use different estimation methods and update frequencies, the reported values were aggregated using an arithmetic mean. This aggregation does not aim to determine statistically representative population parameters, but rather to derive comparable benchmark values that reduce the influence of short-term fluctuations and provider-specific methodological distortions. The arithmetic mean was therefore chosen as a transparent and pragmatic approach to harmonize multiple independent estimates from different sources in the absence of methodological standardization. It is acknowledged that these continuously updated online sources do not always adhere to the traditional standards of academic peer review. Nevertheless, they provide a representation of the current operational state of DLT systems that is more empirically relevant than that obtainable from academic literature alone. Each dataset was cross-checked with additional independent sources where possible, and all sources used in the analysis are systematically documented. To ensure complete transparency and reproducibility, the full derivation of all numerical values used in this study is provided in the Supplementary Material (Stopfer and Buss, 2025). The full calculation process, including data sources, URLs, access data, assumptions, intermediate results, and aggregation procedures, is documented in an accompanying Excel file, which allows the reported results to be independently verified and reused.

## 3 Results

### 3.1 Characteristics, functionality, and applications

#### 3.1.1 Blockchain and distributed ledger technology

As an integrated, multi-layered technology, blockchain can address challenges related to the synchronization of distributed databases and thereby manage the increasing complexity of value chains (Casino et al., 2019; Nikolakis et al., 2018). A blockchain is a continuous series of encrypted blocks containing transaction data, each linked to the preceding block through a cryptographic reference. The creation and exchange of transactions by participants alter the state of the blockchain (Wust and Gervais, 2018), a process that is verified and validated by individual network nodes. All recorded transactions are visible to all participants in the network (Figorilli et al., 2018); however, once registered, they cannot be altered without public consensus (Patelli and Mandrioli, 2020). Subsequent changes are therefore impossible, making blockchain ideal for traceability applications (Sunny et al., 2020). Blockchain is characterized by decentralization, consensus, validity, immutability, and authentication, making it particularly suitable for transparent and verifiable record-keeping. It provides a digital infrastructure that can be used, for example, for mapping forestry and timber supply chains, thereby ensuring data transparency. In addition, synergies and efficiencies can be achieved by connecting cloud resources and IoT devices. The tamper-proof, block-by-block transmission of data, combined with consensus mechanisms (depending on the blockchain type), creates an interconnected data chain (Eberhardt and Tai, 2017).

#### 3.1.2 Complementary technologies

Complementary technologies beyond blockchain are essential for industrial automation and digitization in forestry supply chains. Liu et al. (2023) highlighted the role of the Industrial Internet of Things (IIoT), which uses sensor-based systems to transmit data via wireless sensor networks (WSNs). These systems are typically battery-powered; however, their energy characteristics lie beyond the scope of this study. The volume of data and the transmission distance significantly influence energy use (Amin and Biswas, 2016). Fog computing reduces latency, processing time, and energy consumption by minimizing cloud transfers (Almadhoun et al., 2018). Although IoT-generated data are increasingly abundant and widely accessible, storing them directly on the blockchain remains inefficient due to high transaction costs and energy consumption. With the advent of 5G, large datasets (such as tree images or satellite scans) can be transmitted in near real-time. It is therefore essential to establish clear rules specifying which data are required for chain-of-custody documentation (Rajan et al., 2023).

#### 3.1.3 DLT type, consensus and system

The selection of a DLT system depends on the ledger type, consensus mechanism, and system architecture. Public DLTs offer decentralization, while private and hybrid systems provide greater control. The consensus mechanism directly affects scalability, security, and energy efficiency, and is central to the “blockchain

trilemma,” in which trade-offs must be made among decentralization, security, and scalability. Programming languages and smart contract capabilities also play an essential role.

Public and private blockchains serve distinct purposes, while hybrid models combine elements of both, enabling decentralized data sharing without the need for third parties (Bada et al., 2021). Private blockchains, controlled by a single entity, enable faster transactions but require trust in the provider. They are particularly suitable for supply chain management in sectors such as forestry, where transactions are validated by trusted actors. However, they incur high operational costs and require widespread adoption (Roy et al., 2020). Public blockchains—such as those used in cryptocurrencies—are highly decentralized and transparent but less scalable due to complex consensus mechanisms like Proof-of-Work (PoW) and Proof-of-Stake (PoS) (Hashemi Joo et al., 2020). They are well suited for financial transactions between untrusted parties and require no dedicated infrastructure (Buterin, 2016; Lamela Seijas et al., 2017). Consortium blockchains strike a balance between decentralization and control. Governed by multiple trusted entities, they are particularly suited to industry-specific use cases such as forestry and logistics, combining transparency with flexible governance (kyzy et al., 2021).

In blockchain systems (Table 3), consensus refers to a collectively verified agreement among network participants regarding the validity of transactions. Permissionless blockchains allow anyone to join, validate, and interact with the data, whereas permissioned blockchains (private or consortium) restrict access and are centrally coordinated (Sasikumar et al., 2023). Various consensus algorithms exist to meet different requirements for reliability, fault tolerance, and node synchronization (Masood and Faridi, 2018). These mechanisms differ substantially in computational and energy demands (Wang et al., 2020). Hybrid approaches are also under investigation. The choice of consensus protocol depends on factors such as throughput (transactions per second), decentralization, cost, energy efficiency, and security (Filatovas et al., 2022).

- Proof-of-Work (PoW) is used in Bitcoin and Ethereum (before Ethereum’s transition to Proof-of-Stake). It requires miners to solve complex computational puzzles to add blocks to the blockchain. This process involves finding a nonce that satisfies certain cryptographic conditions, with the difficulty increasing over time to maintain consistent block generation intervals. While PoW offers robust security by making it computationally impractical for malicious actors to alter the blockchain, it is energy-intensive. The computational complexity of these puzzles demands significant processing power from miners, resulting in high energy consumption (Platt et al., 2021). The system’s scalability is also a challenge, as the growing number of miners increases the competition for block creation, further escalating energy costs. Despite its security benefits, PoW’s environmental impact has raised concerns, leading to the exploration of alternative consensus mechanisms like Proof-of-Stake (PoS) and others (Masood and Faridi, 2018).
- Proof-of-Stake (PoS), as used by Ethereum (after its upgrade) and Cardano, allows validators to create new blocks based on the number of tokens they hold and are willing to “stake” as

collateral. Validators are chosen with a weighted probability proportional to the size of their stake, meaning those with larger holdings have a higher chance of being selected. Several variants exist, such as random block selection, where a random function chooses a validator based on the number of tokens staked, and selection by coin age, where the age of the coins also influences the selection (Bachani and Bhattacharjya, 2023). PoS is more energy-efficient than PoW because it does not require competitive computing power. Validators' chances of being selected increase with their stake and the time they hold their tokens, making it a system that rewards long-term participation (Bachani and Bhattacharjya, 2023; Bertino et al., 2021).

- Delegated Proof-of-Stake (DPoS) enhances transaction speed and scalability by allowing stakeholders to vote for delegates, known as witnesses, who are responsible for validating transactions. The number of votes and their weighting determine which witnesses are selected. The system improves throughput by enabling multiple transactions to be included in a block, though a transaction is not confirmed until a certain number of untrusted nodes have verified it. Witnesses are periodically replaced based on ongoing votes, and the size of a stakeholder's share influences the weight of their vote, with larger stakeholders having more influence over the selection process (Bachani and Bhattacharjya, 2023).
- The Proof-of-History (PoS and PoH) is a consensus mechanism used as an example by the Solana blockchain platform. Designed for efficiency and scalability, the mechanism regulates the sequence of events that are validated in a decentralized network. It uses a deterministic timestamping, where timestamp events are linked and stored in chronological order. This timestamping increases efficiency and scalability. A special feature is the combination with PoS. Although PoH determines the sequence of events, the final consensus on the transaction sequence is achieved by PoS as described above. PoS is used to prevent malicious behavior and ensure that the network agrees on the state of the blockchain (Sharma, 2023).
- Practical Byzantine Fault Tolerance (PBFT), used in Hyperledger Fabric and Ripple, is a consensus mechanism mainly designed for permissioned blockchains. It provides fast, scalable, and efficient transaction validation by ensuring that all nodes in the network agree on the state of the ledger, even if some nodes fail or behave maliciously (Zhang et al., 2025). PBFT works through a three-phase process: preparation, commit, and response, where trusted validators periodically confirm the order and validity of transactions. This iterative process ensures that all validators have a consistent view of the ledger. By addressing Byzantine faults (asymmetric information), PBFT prevents the spread of incorrect or manipulated data, achieving consensus with a tolerance threshold of  $(n-1)/3$  in a quorum of correct nodes. This mechanism is particularly suited for systems like Ripple (XRP) and Hyperledger Fabric, where transaction validation and efficiency are paramount (Roma and Anwar Hasan, 2020).
- IOTA-Tangle, primarily designed for Internet of Things (IoT) networks, uses a Directed Acyclic Graph (DAG) structure,

connecting transactions in a non-linear fashion. Unlike Bitcoin's linear Merkle tree, IOTA creates a "tangle" by linking individual transactions without the need for miners, which significantly increases transaction speed (TPS) and reduces energy consumption (Masood and Faridi, 2018). In IOTA, each transaction validates two previous ones, forming a network that avoids loops and improves scalability as the number of transactions grows. Initially, IOTA operated with a centralized coordinator, limiting decentralization, but with IOTA 2.0, this constraint was removed, enabling fully decentralized solutions and the introduction of smart contracts PoW (Sealey et al., 2022). IOTA's low cost, fast transaction times, and high scalability make it highly suitable for IoT applications, such as timber supply chains. However, the requirement for a coordinator to detect faulty nodes remains a drawback (Masood and Faridi, 2018).

## 3.2 DLT system selection overview

The selection of a DLT system depends on the specific objectives of the use case and must consider factors such as the ledger type, consensus mechanism, programming language, and transaction speed (Table 3). These factors significantly influence system performance, energy consumption, and scalability.







For example, Ethereum's Proof-of-Stake (PoS) consensus algorithm is well suited for low-energy applications, whereas IOTA's Directed Acyclic Graph (DAG) architecture is particularly effective for scalable Internet of Things (IoT) scenarios (Sealey et al. 12.09.2022). Public DLTs offer strong decentralization; however, the consensus mechanism should be aligned with the specific requirements of the use case. As demonstrated by multiple studies, the chosen consensus mechanism has a direct impact on system efficiency and sustainability (Bouraga, 2021).

Except for the private Hyperledger Fabric, the DLTs presented include sustainability assessments that evaluate energy use and emissions to determine environmental impact.

## 3.3 Energy consumption of DLT networks

Following a thorough review of the existing literature (Table 1; Figure 1), it was determined that a focused selection of relevant publications would be sufficient for the present study. Consequently, the analysis focuses on studies and media records examining the energy consumption of blockchain systems. Sedlmeir et al. (2020) compared energy use across different consensus mechanisms, highlighting PoW as particularly energy-intensive, whereas alternatives such as PoS and PBFT demonstrated higher efficiency. Redundant data storage was identified as a key factor contributing to network reliability (Arun et al., 2019; Bouraga, 2021; Dobrovnik et al., 2018; Lamriji et al., 2023; Sedlmeir et al., 2020). Bada et al. (2021) developed a categorization system for blockchains based on a traffic light model. PoW systems such as Bitcoin and pre-upgrade Ethereum were rated red (high consumption), while PoS and PBFT systems (common in private and consortium blockchains) were rated green to yellow (low to moderate

TABLE 3 Overview of DLT systems according to literature of chapter 3.3. & 3.4.

| DLT system                           |  <b>bitcoin</b>  |  <b>ethereum</b>  |  <b>CARDANO</b>   |  <b>SOLANA</b>   |  <b>ripple</b>  |  <b>IOTA</b>  |
|--------------------------------------|---|--|--|---|--|--|
| Criteria                             |   |  |  |   |  |  |
| Short description                    | The first and most well-known cryptocurrency. It requires significant computational power for transaction validation and has a structure for secure, decentralized transactions | A decentralized platform that allows for the creation and execution of smart contracts and decentralized applications, enabling a wide range of functionalities beyond simple transactions | A proof-of-stake blockchain platform focused on a scientific approach to design, supporting smart contracts and aiming for a more secure and scalable environment for decentralized applications | A high-performance platform utilizing a unique consensus mechanism to achieve high throughput and low transaction costs, ideal for decentralized applications and smart contracts | A digital payment protocol and cryptocurrency designed for fast, low-cost international transfers, using a unique consensus algorithm for secure transactions across its network | A DLT designed for the internet of things (IoT), using a unique structure, a directed acyclic graph (DAG), called the tangle that enables feeless transactions and high scalability without traditional mining |
| Foundation (Year)                    | Bitcoin.org (2008)  | Ethereum Foundation (2015)   | Cardano foundation (2015)  | Solana Foundation (2023)  | Ripple Labs (2013)   | IOTA foundation (2015)   |
| Consensus                            | Proof-of-Work (PoW)   | Proof-of-stake (PoS) [until 2022 POW]  | Ouroboros (a variant of PoS)   | Proof-of-history (PoH) combined with proof-of-stake (PoS)   | Ripple protocol consensus algorithm (RPCA, a variant of PBFT)  | Tangle (uses a directed acyclic graph, DAG)  |
| Programming language                 | Bitcoin script (a simple stack-based language for transactions)   | Solidity (JavaScript-like language for the ethereum virtual machine EVM)   | Plutus (for smart contracts), haskell (for platform development)   | Rust, C, and C++ (for smart contracts and platform development)   | Custom scripting language (supports various languages: Java, JavaScript and C++)   | Unique programming language that supports C, rust, Python and C++  |
| Average transaction per second (TPS) | Approx. 7 TPS   | Approx. 16,5 TPS   | Approx. 5,7 TPS  | Average 50.000 TPS  | Approx. 1.500 TPS  | Theoretically unbounded; typically around 1.000 TPS  |
| Crypto currency                      | Bitcoin (BTC)   | Ether  | ADA  | SOL   | XRP  | MIOTA  |

consumption) (Bada et al., 2021; Sarkodie et al., 2023). Siddik et al. (2023) compared Bitcoin’s energy, water, and CO<sub>2</sub> impact with that of traditional monetary systems, emphasizing the role of green energy and consensus types. Kohli et al. (2022) concentrated on energy consumption per transaction and the impact of mining hardware across different countries (Kohli et al., 2022). Platt et al. (2021) provided the most detailed comparison of blockchains such as Algorand, Cardano, Tezos, Ethereum 2.0 and Bitcoin, alongside VisaNet, in terms of total and per-transaction energy use. For context, a Google search uses approximately 0.0003 kWh, while a ChatGPT search uses around 0.003 kWh (Eva-Maria Weiß, 2024).

A comprehensive assessment of the sustainability of blockchain systems must therefore take numerous aspects into account:

- Influence of the consensus mechanism
- Mining infrastructure used with mining devices
- Geographic distribution of blockchain network nodes
- Energy mix of the countries hosting these nodes

Building upon the findings from previous research, this study advances the analysis by incorporating real-time network data to evaluate energy consumption per transaction. Considering the heterogeneity of national energy mixes (e.g., gas, coal, nuclear) and the scarcity of consistent mining infrastructure data, the methodological focus is therefore limited to transaction-level energy consumption of selected DLT systems (Siddik et al., 2023). The values for the required parameters were obtained from the Crypto Sustainability Metrics page, which is updated on

a daily basis. To verify the proportions of the values, the authors double-checked the information from other sources (CCRI, 2025). When selecting data sources, consistency and replicability were prioritized. Each dataset on transaction-level or network-wide energy use was verified against independent providers (Carbon Footprint Ltd, 2024; Electricity Maps ApS, 2025). This procedure also applied to related parameters such as transaction price and throughput (TPS). The first overview focuses on total network energy use, overall emissions, and total transactions. Table 4 summarizes the compiled system-level data, presenting average ranges derived from multiple independent sources to account for methodological discrepancies and temporal variations (Ethereum Foundation, 2025; Platt et al., 2021; Sedlmeir et al., 2020).

Building on Table 4, Table 5 extends the dataset by adding derived values per transaction and per node to facilitate efficiency comparison.

To translate network energy consumption into emission values, Table 6 summarizes country-specific emission factors (gCO<sub>2</sub>e/kWh) for each nation hosting network nodes. This data serves as the basis for calculating node-related sustainability.

These emission factors were derived from the mean values of three independent data providers to ensure methodological reliability and comparability.

As demonstrated energy consumption is largely determined by the consensus mechanism. PoS utilises significantly less energy than PoW, with a reduction of over 99%. Other key factors to consider include network traffic, hash rate, and transaction size (Lamriji et al., 2023; Nguyen et al., 2019; Sapra and Shaikh, 2023). DAG-based

TABLE 4 Overview of different blockchain systems according to power consumption, emissions and transactions (bitinfocharts.com, 2025; CCRI, 2025; explorer.io, 2025; explorer.iota.org, 2025; solscan.io, 2025; xrpscan.com, 2025; ycharts.com, 2025).

| Blockchain-system | Annual network energy consumption (9.11.25) | Total Transaction (extrapolated from 09.11.2025) | Total CO2e-emissions per network (9.11.2025) | gCO2e-emissions per transaction (9.11.2025) |
|-------------------|---|--|--|---|
|                   | [kWh/a]                                     | [tx]   | [t CO2e]                                     | [g CO2e/tx]                                 |
| Bitcoin           | 177,800,000,000                             | 170,165,190                                      | 69,990,000.00                                | 411,306.21                                  |
| Ethereum          | 4,298,270                                   | 532,279,500                                      | 1313.39                                      | 2.47  |
| Cardano           | 436,900                                     | 28,200,995                                       | 149.88                                       | 5.31  |
| Solana            | 16,511,760                                  | 91,512,263,085                                   | 5075.04                                      | 0.06  |
| Ripple            | 471,770                                     | 390,412,760                                      | 194.18                                       | 0.50  |
| Iota              | 217,810                                     | 697,150,000                                      | 56.47  | 0.08  |

TABLE 5 Overview of different systems according to calculated values per transaction and node basis (based on (Alexander Shishkanov, 2025; coinbase.com, 2025; coindocx.com, 2025; etherscan, 2025; gasfees.org, 2025; iota-services.com, 2025; Jennifer Alanis, 2025; theblock.co, 2025; ycharts.com, 2025).

| Blockchain-system | Energy consumption per transaction | Number of nodes for each network | Energy per Network Node per year | Energy per network node per h | Mean price per transaction |
|-------------------|------------------------------------|----------------------------------|----------------------------------|-------------------------------|----------------------------|
|                   | [kWh/tx]                           | Numbers                          | [kWh/Node/a]                     | kWh/node/h                    | [\$/Tx]                    |
| Bitcoin           | 1044.9                             | 68,192                           | 2,607,343.97                     | 297.6420                      | 1.0120                     |
| Ethereum          | 0.0081                             | 9,040                            | 475.47                           | 0.0543                        | 0.5590                     |
| Cardano           | 0.0155                             | 2,868                            | 152.34                           | 0.0174                        | 0.0952                     |
| Solana            | 0.0002                             | 5,850                            | 2,822.52                         | 0.3222                        | 0.0015                     |
| Ripple            | 0.0012                             | 889                              | 530.67                           | 0.0606                        | 0.0009                     |
| Iota              | 0.0003                             | Undefined                        | Undefined                        | Undefined                     | 0                          |

TABLE 6 Overview of emissions of gCO2e per kWh (based on Electricity Maps ApS, 2025; Ritchie et al., 2024; Carbon Footprint Ltd, 2024).

| Country |             | gCO2e/kWh | Country |                | gCO2e/kWh | Country        |             | gCO2e/kWh |
|---------|-------------|-----------|---------|----------------|-----------|----------------|-------------|-----------|
| IND     | India       | 774.60    | EST     | Estonia        | 433.86    | AUT            | Spain       | 160.04    |
| POL     | Poland      | 698.98    | GER     | Germany        | 384.6     | CAN            | Canada      | 143.0     |
| HKG     | Hong Kong   | 695.97    | USA     | USA            | 371.79    | FIN            | Finland     | 88.34     |
| CHN     | China       | 621.4     | ITA     | Italy          | 346.3     | BRA            | Brazil      | 80.8      |
| AUS     | Australia   | 566.71    | IRL     | Ireland        | 338.04    | FRA            | France      | 57.18     |
| SGP     | Singapore   | 486.83    | NLD     | Netherlands    | 313.00    | CHE            | Switzerland | 43.23     |
| JPN     | Japan       | 467.47    | GBR     | United Kingdom | 221.80    | SWE            | Sweden      | 25.64     |
| RUS     | Russia      | 448.5     | LTU     | Lithuania      | 169.75    | NOR            | Norway      | 22.95     |
| KOR     | South Korea | 439.52    | ESP     | Austria        | 165.8     | *World Average |             | 481.00    |

systems offer even greater efficiency, enabling faster, cheaper, and more energy-saving transactions (Kably et al., 2022).

Power consumption, emissions, and transaction volume of DLTs like Bitcoin, Ethereum, Ripple, Cardano, Solana, and IOTA vary due to differences in consensus mechanisms and network architecture, and can fluctuate with time and crypto exchange rates:

Bitcoin uses the energy-intensive PoW mechanism, resulting in high consumption, estimated at 177.8 TWh per year and 1,044.9 kWh, with a mean transaction cost of \$1.01. This leads to approximately 411,306 kgCO2e per transaction, making Bitcoin by far the most emission-intensive DLT. Its relatively low throughput of up to 7 transactions per second (TPS) further amplifies its

environmental footprint (Fartitchou et al., 2024; Masood and Faridi, 2018; Popov and Lu, 2019; Sarkodie et al., 2023).

Ethereum, after its switch to Proof-of-Stake (PoS) in 2022, has achieved a reduction in energy use, consuming only 0.0081 kWh per transaction and producing 2.47 gCO<sub>2</sub>e per transaction, at a mean cost of \$0.56. With an estimated 532 million transactions per year and a network of about 9,040 nodes, the annual energy consumption amounts to roughly 4.3 GWh (Cambridge University, 204; CCRI, 2025; CoinPedia, 2023; Cointelgraph, 2022; Ethereum, 2023; Author anonymous, 2016; Forbesindia, 2024; MoneySuperMarket, 2022; MONY Group Financial Limited, 2024; Platt et al., 2021; Sedlmeir et al., 2020; Fartitchou et al., 2024; Rana et al., 2024; Monem et al., 2024; Rao et al., 2024).

Similarly, Cardano (PoS-based) requires only 0.0155 kWh per transaction and 5.31 g CO<sub>2</sub>e per transaction, with a mean cost of \$0.095. Operating with about 2,868 nodes, its total network energy consumption is 436.9 MWh per year, corresponding to approximately 152.34 kWh per node annually. The protocol supports a TPS of around 5.7 (CoinPedia, 2023; MoneySuperMarket, 2022; Platt et al., 2021; TRG Datacenters, 2024) It will reach up to TPS rate of 5.7 (Quattrocchi et al., 2024).

Solana combines Proof-of-Stake (PoS) and Proof-of-History (PoH) mechanisms, achieving both high speed and low energy use. It consumes merely 0.0002 kWh per transaction and 0.06 g CO<sub>2</sub>e per transaction, with a mean cost of \$0.0015. Despite a relatively large node count of about 5,850, its efficiency is remarkable: each node consumes roughly 2,822.52 kWh per year. Solana supports between 50,000 and over 700,000 TPS, representing one of the most scalable DLT architectures (Coincodex, 2024; Quattrocchi et al., 2024; Saini, 2023; SafeCoin, 2022; Sharma, 2023; Solana Foundation, 2023).

Ripple, using the Ripple Protocol Consensus Algorithm (RPCA), demonstrates exceptional energy efficiency with 0.0012 kWh per transaction and only 0.50 g CO<sub>2</sub>e per transaction, at a mean cost of \$0.0009. With fewer than 900 nodes, the total annual energy use remains below 0.5 GWh, while throughput reaches up to 1,500 TPS, comparable to the Visa network (MoneySuperMarket, 2022; TRG Datacenters, 2024).

IOTA's Directed Acyclic Graph (DAG)-based "Tangle" system operates without miners and therefore consumes extremely little energy around 0.0003 kWh per transaction, corresponding to 0.08 g CO<sub>2</sub>e per transaction and zero transaction fees. Although the exact number of nodes is undefined, its architecture allows 1,000 TPS or more, theoretically without upper limit (Amir Abbaszadeh Sori, 2019; Corporate Crypto, 2023; Fartitchou et al., 2024; Gligoric et al., 2024; Iota Hispano, 2024; Popov and Lu, 2019; Quattrocchi et al., 2024; Sori et al., 2020; TRG Datacenters, 2024; Wiki Iota, 2024).

The comparative results presented in Tables 4 and 5 reveal how different consensus mechanisms and network architectures lead to varying outcomes, illustrating the blockchain trilemma of balancing decentralization, security, and scalability. Bitcoin prioritizes security and decentralization but struggles with scalability. Newer solutions such as PoS, DAG (e.g., IOTA), sharding and Layer 2 aim to resolve these trade-offs (Bada et al., 2021; Sori et al., 2020).

While Bitcoin remains the most energy-intensive DLT, alternatives such as Ethereum, Cardano, Ripple, Solana, and IOTA demonstrate improved efficiency and scalability (Bouraga, 2021). It is evident that the trend is moving towards more

sustainable blockchain models, although the long-term environmental impact of these models will be shaped by factors such as adoption, technological development, and regulatory frameworks. Having established the energy characteristics of the selected DLT systems, the following section examines their carbon intensity. Section 3.4 integrates node distribution, national energy profiles, and emission factors to evaluate the environmental footprint of five major blockchain networks, excluding IOTA due to its decentralized DAG structure, which prevents geographically traceable validation processes.

### 3.4 Emissions of DLT networks

A detailed analysis examines blockchain systems by country-level node distribution and associated emissions. The number of nodes was obtained from the blockchain system operators' websites, as these contain the most up-to-date information. While independent sources have confirmed the approximate number of nodes, it should be noted that the node counts represent temporal snapshot. Although these sources constitute grey literature, their continuous updates and transparent methodologies provide higher temporal accuracy than many peer-reviewed publications, which frequently rely on static or outdated figures. To minimize potential bias, the mean value of three independent sources was used to enhance robustness and comparability. Additionally, Oxford University, as an academic authority, operates the website 'Our World in Data' and provides CO<sub>2</sub>e values for each country. The other two sources are licensed providers of country comparisons regarding the electricity mix. These sources are used to report scope-related electricity emissions. As the accuracy of the figures provided by all three sources cannot be fully verified, the mean value was used (Coincodex, 2024; CoinPedia, 2023; Cointelgraph, 2022; Corporate Crypto, 2023; Ethereum Foundation, 2023; Forbesindia, 2024; Iota Hispano, 2024; Kumar Rana et al., 2024; MoneySuperMarket, 2022; Platt et al., 2021; Roma and Anwar Hasan, 2020; Solana Compass, 2025; Solana Foundation, 2023; Sori et al., 2020; TRG Datacenters, 2024; Bithomp, 2025).

The top 15 countries, representing at least 80% of total computing power, are summarized in Table 6, showing average CO<sub>2</sub> emissions per kWh based on data from three sources (Carbon Footprint Ltd, 2024; Electricity Maps ApS, 2025; Ritchie et al., 2024). This section focuses on the sustainability of five DLTs. A full CO<sub>2</sub>e assessment considers system size (number and location of nodes), total energy use, and average energy per node (see Tables 4–9). IOTA is excluded from this analysis because its unique DAG-based architecture lacks a stable and geographically traceable node distribution, rendering country-level emissions attribution infeasible. Since node locations span countries with varying energy mixes, emission levels differ. For example, countries with coal-intensive electricity generation, such as India, exhibits higher CO<sub>2</sub>e intensities per kWh, while Sweden and Norway, powered by hydro and renewables, rank lowest.

Table 7 shows Bitcoin remains the most energy- and carbon-intensive DLT among the systems analyzed, emitting on average 411 kg CO<sub>2</sub>e per transaction, with large regional differences depending on node location and energy mix. Transactions in China are about 46% more carbon-intensive than average, while

TABLE 7 Distribution of nodes (10.02.2025) of the Bitcoin network (Bitnodes 2025).

|         | Top 15 Country          |                | Nodes         |          | Average Emissions per energy by Country | Total network energy consumption (09.11.25) |               | CO2e Emissions per transaction [kgCO2e/tx] |
|---------|-------------------------|----------------|---------------|----------|---|---|---------------|--|
|         | [Distribution of nodes] |                | %             | Absolute | [gCO2e/kWh]                             | By Country [t]                              | %             | Average for the network                    |
| Bitcoin | <b>USA</b>              | USA            | <b>23.10%</b> | 15,752   | 371.8                                   | 15,269,934                                  | <b>21.82%</b> | <b>411.306</b>                             |
|         | <b>GER</b>              | Germany        | <b>9.99%</b>  | 6,813    | 384.6                                   | 6,832,854                                   | <b>9.76%</b>  |  |
|         | <b>FRA</b>              | France         | <b>3.42%</b>  | 2,333    | 57.2                                    | 347,847                                     | <b>0.50%</b>  |  |
|         | <b>CAN</b>              | Canada         | <b>3.33%</b>  | 2,271    | 143.0                                   | 846,742                                     | <b>1.21%</b>  |  |
|         | <b>GBR</b>              | United Kingdom | <b>2.60%</b>  | 1,771    | 221.8                                   | 1,024,198                                   | <b>1.46%</b>  |  |
|         | <b>NLD</b>              | Netherlands    | <b>2.51%</b>  | 1,710    | 313.0                                   | 1,395,551                                   | <b>1.99%</b>  |  |
|         | <b>CHN</b>              | China          | <b>2.13%</b>  | 1,451    | 621.4                                   | 2,350,922                                   | <b>3.36%</b>  |  |
|         | <b>AUS</b>              | Australia      | <b>1.99%</b>  | 1,357    | 566.7                                   | 2,005,103                                   | <b>2.86%</b>  |  |
|         | <b>CHE</b>              | Switzerland    | <b>1.77%</b>  | 1,205    | 43.2                                    | 135,817                                     | <b>0.19%</b>  |  |
|         | <b>ESP</b>              | Spain          | <b>1.68%</b>  | 1,145    | 160.0                                   | 477,774                                     | <b>0.68%</b>  |  |
|         | <b>ITA</b>              | Italy          | <b>1.61%</b>  | 1,099    | 346.3                                   | 992,233                                     | <b>1.42%</b>  |  |
|         | <b>RUS</b>              | Russia         | <b>1.60%</b>  | 1,090    | 448.5                                   | 1,274,555                                   | <b>1.82%</b>  |  |
|         | <b>BRA</b>              | Brazil         | <b>1.36%</b>  | 926      | 80.8                                    | 195,040                                     | <b>0.28%</b>  |  |
|         | <b>FIN</b>              | Finland        | <b>1.29%</b>  | 883      | 88.3                                    | 203,380                                     | <b>0.29%</b>  |  |
|         | <b>JPN</b>              | Japan          | <b>1.01%</b>  | 690      | 467.5                                   | 841,004                                     | <b>1.20%</b>  |  |
|         | Other                   | <b>40.61%</b>  | 27,696        | 481.0    | 34,734,452                              | <b>49.63%</b>                               |               |  |
|         | Total                   | <b>100%</b>    | <b>68,192</b> |          | <b>69,990,000</b>                       | <b>100%</b>                                 |               |  |

Bold values indicate percentage distribution of nodes within the Bitcoin network by country.

those in Switzerland emit nearly 90% lower. These results show that geographically cleaner energy sources can significantly reduce Bitcoin’s overall carbon footprint and support more sustainable network operation.

Ethereum’s transition to Proof-of-Stake has drastically reduced its environmental impact, resulting in an average of only 2.47 g CO<sub>2</sub>e per transaction and total annual emissions of 1,313 t CO<sub>2</sub>e. Most nodes are located in the USA (31.6%) and Germany (15.0%), while countries with cleaner energy mixes such as France, Finland, and Switzerland show the lowest emission intensities. Overall, Ethereum demonstrates how PoS-based consensus mechanism can combine scalability with a minimal carbon footprint (Table 8).

The Cardano network (Table 9), with 2,868 nodes, emits 5.32 g CO<sub>2</sub>e per transaction and 149.9 t CO<sub>2</sub>e annually. Most nodes are located in Germany and the USA, accounting for nearly 60% of total emissions. Although Cardano’s overall footprint is low, regional energy intensity makes it the most carbon-intensive PoS system among the analyzed blockchains.

The Solana network (Table 10) operates with 5,850 nodes and records total annual emissions of 5,075 t CO<sub>2</sub>e, corresponding to only 0.055 g CO<sub>2</sub>e per transaction, which is the lowest value among the DLTs analyzed. Most nodes are in the USA (30.6%) and Germany (20.0%), together accounting for more than 32% of

total emissions. In contrast, countries with low-carbon electricity mixes such as France, Norway, and Sweden contribute less than 1% each. Solana’s hybrid PoS and PoH consensus enables very high transaction throughput with minimal energy use, positioning the network among the most carbon-efficient blockchain systems currently in operation (Nguyen et al., 2019).

The Ripple (XRP) network (Table 11), with 889 nodes, achieves exceptionally low emissions of only 0.497 g CO<sub>2</sub>e per transaction and 194 t CO<sub>2</sub>e per year. Most nodes are located in the USA (21.8%) and Germany (11.8%), while regions with cleaner energy, such as Finland and Switzerland, show the lowest carbon intensities. Ripple’s efficient RPCA consensus enables high throughput with minimal energy use, underscoring its strong sustainability performance among major DLT systems.

This analysis highlights the critical role of locating nodes and processing transactions in low emission regions to minimize blockchain’s overall environmental footprint. At the same time, maintaining a geographically diverse node distribution is essential for network resilience and decentralization. Concentrating nodes in low-carbon regions (commonly seen in parts of Europe) can increase exposure to regional grid instabilities. Accordingly, node placement represents a relevant lever for improving the environmental performance of blockchain systems, though in practice, economic factors such as electricity prices, carbon taxes,

TABLE 8 Distribution of nodes (10.02.2025) of the Ethereum (ethernodes.org 2025; etherscan 2025; Eth2 Nodewatch 2025).

|          | Top 15 Country          |                | Nodes         |          | Average emissions per energy by Country | Total network energy consumption (09.11.25) |               | CO2e emissions per transaction [gCO2e/tx] |
|----------|-------------------------|----------------|---------------|----------|---|---|---------------|---|
|          | [Distribution of nodes] |                | %             | Absolute | [gCO2e/kWh]                             | By Country [t]                              | %             | Average for the network                   |
| Ethereum | USA                     | USA            | <b>31.62%</b> | 2,858    | 371.8                                   | 505.23                                      | <b>38.47%</b> | <b>2.467</b>                              |
|          | GER                     | Germany        | <b>14.97%</b> | 1,353    | 384.6                                   | 247.45                                      | <b>18.84%</b> |   |
|          | FIN                     | Finland        | <b>6.11%</b>  | 552      | 88.3                                    | 23.19                                       | <b>1.77%</b>  |   |
|          | FRA                     | France         | <b>5.87%</b>  | 531      | 57.2                                    | 14.44                                       | <b>1.10%</b>  |   |
|          | GBR                     | United Kingdom | <b>4.18%</b>  | 378      | 221.8                                   | 39.86                                       | <b>3.04%</b>  |   |
|          | SGP                     | Singapore      | <b>3.86%</b>  | 349      | 486.8                                   | 80.78                                       | <b>6.15%</b>  |   |
|          | CAN                     | Canada         | <b>3.48%</b>  | 315      | 143.0                                   | 21.42                                       | <b>1.63%</b>  |   |
|          | NLD                     | Netherlands    | <b>2.84%</b>  | 257      | 313.0                                   | 38.25                                       | <b>2.91%</b>  |   |
|          | JPN                     | Japan          | <b>2.81%</b>  | 254      | 467.5                                   | 56.46                                       | <b>4.30%</b>  |   |
|          | KOR                     | South Korea    | <b>2.36%</b>  | 213      | 439.5                                   | 44.51                                       | <b>3.39%</b>  |   |
|          | IRL                     | Ireland        | <b>2.11%</b>  | 191      | 338.0                                   | 30.70                                       | <b>2.34%</b>  |   |
|          | AUT                     | Austria        | <b>1.92%</b>  | 174      | 165.8                                   | 13.72                                       | <b>1.04%</b>  |   |
|          | CHE                     | Switzerland    | <b>1.77%</b>  | 160      | 43.2                                    | 3.29  | <b>0.25%</b>  |   |
|          | CHN                     | China          | <b>1.13%</b>  | 102      | 621.4                                   | 30.14                                       | <b>2.29%</b>  |   |
|          | POL                     | Poland         | <b>1.10%</b>  | 99       | 699.0                                   | 32.90                                       | <b>2.51%</b>  |   |
|          | Other                   | <b>13.87%</b>  | 1,254         | 481.0    | 286.79                                  | <b>21.84%</b>                               |               |   |
|          | Total                   | <b>100%</b>    | <b>9,040</b>  |          | <b>1,313.39</b>                         | <b>100%</b>                                 |               |   |

Bold values indicate percentage distribution of nodes within the Ethereum network by country.

and financial incentives often outweigh purely environmental considerations.

### 4 Modelling a timber supply chain

Global timber supply chains are highly complex socio-technical systems involving numerous stakeholders operating across multiple jurisdictions. This complexity renders them particularly susceptible to fraudulent practices, such as the mislabeling of illegally harvested or unsustainably sourced timber as certified material (Fabing, 2021). To address these risks, traceability systems have been developed to document and verify the movement of timber from forest operations through processing to final consumption (Kravets et al., 2015). Over time, such systems have become a core component of sustainable forest management and regulatory compliance, supported by international frameworks such as ISO 9001 and the St. Petersburg Ministerial Declaration (2005), which explicitly promote third-party-verifiable mechanisms to combat illegal logging and enhance transparency (Savino et al., 2017). In response to these requirements, this study models a realistic timber supply chain within clearly defined system boundaries, extending from standing trees in the forest to the entrance of the sawmill. The modeled actors include forest owners or concession

holders, logging companies, forest logistics operators (including forwarders and truck drivers), sawmills, and public authorities or certification bodies such as the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). In addition, the model explicitly accounts for regulatory enforcement bodies responsible for implementing the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), the EU Timber Regulation (EUTR), the EU Deforestation Regulation (EUDR), and the Lacey Act (FSC Deutschland, 2025). These actors and regulations jointly define the institutional, technical, and data requirements for timber traceability.

#### 4.1 Log identification

In the proposed model, timber is digitally represented at the level of individual trees and logs by Digital Product Passports (DPPs), which act as permanent digital records throughout the supply chain (Albert et al., 2025). DPPs enable fine-grained traceability while avoiding the direct storage of large datasets on the blockchain (Figure 2). The reliability of blockchain-based timber traceability depends critically on robust log identification technologies that ensure a stable and verifiable link between physical logs and their digital representations. Following

TABLE 9 Distribution of nodes (10.02.2025) of the Cardano network (explorer 2025).

|         | Top 15 Country          |                | Nodes  |          | Average emissions per Energy by Country | Total network energy consumption (09.11.25) |        | CO2e emissions per transaction [gCO2e/tx] |
|---------|-------------------------|----------------|--------|----------|---|---|--------|---|
|         | [Distribution of nodes] |                | %      | Absolute | [gCO2e/kWh]                             | By Country [t]                              | %      | Average for the network                   |
| Cardano | GER                     | Germany        | 27.44% | 787      | 384.6                                   | 46.12                                       | 30.77% | 5.315                                     |
|         | USA                     | USA            | 25.91% | 743      | 371.8                                   | 42.08                                       | 28.08% |   |
|         | GBR                     | United Kingdom | 6.07%  | 174      | 221.8                                   | 5.88  | 3.92%  |   |
|         | NLD                     | Netherlands    | 4.95%  | 142      | 313.0                                   | 6.77  | 4.52%  |   |
|         | FRA                     | France         | 3.94%  | 113      | 57.2                                    | 0.98  | 0.66%  |   |
|         | JPN                     | Japan          | 4.57%  | 131      | 467.5                                   | 9.33  | 6.22%  |   |
|         | CAN                     | Canada         | 5.37%  | 154      | 143.0                                   | 3.35  | 2.24%  |   |
|         | SWE                     | Sweden         | 1.32%  | 38       | 25.6                                    | 0.15  | 0.10%  |   |
|         | FIN                     | Finland        | 3.52%  | 101      | 88.3                                    | 1.36  | 0.91%  |   |
|         | IRL                     | Ireland        | 1.29%  | 37       | 338.0                                   | 1.91  | 1.27%  |   |
|         | KOR                     | South Korea    | 1.85%  | 53       | 439.5                                   | 3.55  | 2.37%  |   |
|         | AUS                     | Australia      | 1.74%  | 50       | 566.7                                   | 4.32  | 2.88%  |   |
|         | IND                     | India          | 1.08%  | 31       | 774.6                                   | 3.66  | 2.44%  |   |
|         | SGP                     | Singapore      | 2.16%  | 62       | 486.8                                   | 4.60  | 3.07%  |   |
|         | AUT                     | Austria        | 0.91%  | 26       | 165.8                                   | 0.66  | 0.44%  |   |
|         | Other                   | 7.88%          | 226    | 481.0    | 16.56                                   | 11.05%                                      |        |   |
|         | Total                   | 100%           | 2,868  |          | 149.88                                  | 100%  |        |   |

Bold values indicate percentage distribution of nodes within the Cardano network by country.

Kaulen et al. (2024), identification approaches can be categorized as either active, involving methods such as paint markings, hammer imprints, RFID tags, and optical codes, or passive, relying on the wood’s intrinsic characteristics, including its optical, chemical, or genetic properties. Optical identification methods (Figure 3), particularly biometric fingerprinting of the log cross-section, have been shown to be well suited for operational deployment. These methods allow for unique and repeatable identification in harsh field conditions and support automated data acquisition without the need for additional physical markers. To be compatible with distributed ledger technologies, identification systems must be standardized, cost-effective, and robust, while enabling automated data capture and minimizing errors arising from manual data transfer. Current research indicates that optical identification methods, whether active or passive, meet these requirements for full integration into blockchain-based timber tracking systems at scale (Elias, 2024; Kaulen et al., 2024).

### 4.2 Transaction model and ethereum-based notarization

To contextualize the proposed transaction model within real forestry operations, the timber supply chain is conceptualized as a sequence of discrete physical state changes of a functional unit. This

unit is defined as either a single log or a specific assortment of logs. Blockchain technology is employed not as a continuous data storage layer but rather as a selective notarization mechanism that documents only those process events at which the timber’s state or location changes in a manner relevant to traceability, certification, or regulatory verification. The pilot implementation reflects the decentralized governance structure common in Central European forestry. The Forest Owners’ Association Schwarzwald acted as the forest owner and contracting entity. Independent private contractors carried out timber harvesting and forwarding using fully mechanized cut-to-length (CTL) systems, as well as motor-manual harvesting where required. A separate logistics company performed transport from the forest road to the processing facility, and the sawmill Streit represented downstream processing as the receiving entity at the mill gate and infeed. Although certification bodies and regulatory frameworks provided the institutional context, they did not actively generate transactions within the pilot. Within this framework, traceability was implemented using a six-event transaction model that aligns with CTL harvesting procedures and established forestry data standards. A blockchain transaction is generated whenever a log is physically manipulated or relocated, thereby altering its state or position within the supply chain, as illustrated in Figure 4. This transaction set represents a realistic and operationally sufficient baseline for end-to-end

TABLE 10 Distribution of nodes (10.02.2025) of the Solana (Solana Compass, 2025).

|        | Top 15 Country          |                | Nodes         |          | Average Emissions per Energy by Country | Total network energy consumption (09.11.25) |               | CO2e Emissions per transaction [gCO2e/tx] |
|--------|-------------------------|----------------|---------------|----------|---|---|---------------|---|
|        | [Distribution of nodes] |                | %             | Absolute | [gCO2e/kWh]                             | By Country [t]                              | %             | Average for the network                   |
| Solana | USA                     | USA            | <b>30.55%</b> | 787      | 371.8                                   | 825.88                                      | <b>16.27%</b> | <b>0.055</b>                              |
|        | GER                     | Germany        | <b>20.00%</b> | 743      | 384.6                                   | 806.66                                      | <b>15.89%</b> |   |
|        | NLD                     | Netherlands    | <b>12.10%</b> | 174      | 313.0                                   | 153.72                                      | <b>3.03%</b>  |   |
|        | FRA                     | France         | <b>5.83%</b>  | 142      | 57.2                                    | 22.92                                       | <b>0.45%</b>  |   |
|        | CAN                     | Canada         | <b>5.78%</b>  | 113      | 143.0                                   | 45.61                                       | <b>0.90%</b>  |   |
|        | JPN                     | Japan          | <b>5.33%</b>  | 131      | 467.5                                   | 172.85                                      | <b>3.41%</b>  |   |
|        | SGP                     | Singapore      | <b>4.09%</b>  | 154      | 486.8                                   | 211.61                                      | <b>4.17%</b>  |   |
|        | GBR                     | United Kingdom | <b>4.07%</b>  | 38       | 221.8                                   | 23.79                                       | <b>0.47%</b>  |   |
|        | LTU                     | Lithuania      | <b>1.13%</b>  | 101      | 169.8                                   | 48.39                                       | <b>0.95%</b>  |   |
|        | IRL                     | Ireland        | <b>1.11%</b>  | 37       | 338.0                                   | 35.30                                       | <b>0.70%</b>  |   |
|        | RUS                     | Russia         | <b>0.74%</b>  | 53       | 448.5                                   | 67.09                                       | <b>1.32%</b>  |   |
|        | NOR                     | Norway         | <b>0.62%</b>  | 50       | 22.9                                    | 3.24  | <b>0.06%</b>  |   |
|        | POL                     | Poland         | <b>0.56%</b>  | 31       | 699.0                                   | 61.16                                       | <b>1.21%</b>  |   |
|        | HKG                     | Hong Kong      | <b>0.53%</b>  | 62       | 696.0                                   | 121.79                                      | <b>2.40%</b>  |   |
|        | SWE                     | Sweden         | <b>0.51%</b>  | 26       | 25.6                                    | 1.88  | <b>0.04%</b>  |   |
|        | Other                   | <b>7.06%</b>   | 3,208         | 481.0    | 235.06                                  | <b>4.63%</b>                                |               |   |
|        | Total                   | <b>100%</b>    | <b>5,850</b>  |          | <b>5,075.04</b>                         | <b>100%</b>                                 |               |   |

Bold values indicate percentage distribution of nodes within the Solana network by country.

traceability from standing trees to mill infeeds (Kaulen et al., 2024; Stopfer et al., 2024).

The six events comprise:

- Recording of standing tree information and the felling event (forest stand)
- Cutting into assortments (Skid Road)
- Forwarding of timber (Forest Road)
- Loading onto a lorry (Forest Road)
- Transport and unloading (Sawmill)
- Placement on the infeed table before processing (Sawmill)

Initial data capture takes place at the harvesting site and is extended incrementally at each subsequent processing stage. For each event, the blockchain records cryptographic hashes and minimal metadata, including geospatial coordinate hashes, timestamps, visual evidence of the log cross-section and volumetric attributes such as length, diameter, and calculated volume. Detailed operational data, such as images, measurement records, certificates and transport documents, are stored off-chain in a cloud-based data management system implemented by project partner Xylene and referenced on-chain via cryptographic hash pointers. Transactions were submitted by the operational actor (Xylene) and consensus was performed by the public Ethereum

network under Proof-of-Stake (xylene.io, 2025). This hybrid on-chain/off-chain architecture ensures reproducibility and auditability, as all off-chain data can be verified independently at any time by re-computing the hashes and comparing them with the immutable blockchain records. This approach supports key requirements of the EU Deforestation Regulation (EUDR), including geolocation-based verification, volume traceability and verifiable proof of deforestation-free origin, thanks to tamper-resistant records. To empirically validate the proposed model, an Ethereum-based blockchain notarization process was implemented and tested in a pilot application conducted in May 2024 in the Black Forest in Baden-Württemberg, Germany. Ethereum was selected due to its maturity, widespread adoption, and transition to a Proof-of-Stake consensus mechanism, which significantly reduces energy consumption compared to Proof-of-Work systems (Ethereum Foundation, 2025; Ozyilmaz and Yurdakul, 2019). During the pilot, only cryptographic hashes and minimal metadata were notarized on-chain, while detailed operational data remained off-chain. Biometric fingerprint matching was provided by Tracy AB (Sweden), an industrial project partner that supplied the optical identification technology. Xylene implemented and operated the Ethereum-based authentication infrastructure used for notarization.

The pilot covered both fully mechanized CTL harvesting and motor-manual felling, reflecting typical European forestry

TABLE 11 Distribution of nodes (10.02.2025) of the Ripple (Bithomp, 2025).

|              | Top 15 Country          |                | Nodes         |          | Average Emissions per Energy by Country | Total network energy consumption (09.11.25) |               | CO2e Emissions per transaction [gCO2e/tx] |
|--------------|-------------------------|----------------|---------------|----------|---|---|---------------|---|
|              | [Distribution of nodes] |                | %             | Absolute | [gCO2e/kWh]                             | By Country [t]                              | %             | Average for the network                   |
| Ripple (XRP) | USA                     | USA            | <b>21.82%</b> | 194      | 371.8                                   | 38.28                                       | <b>19.71%</b> | <b>0.497</b>                              |
|              | GER                     | Germany        | <b>11.81%</b> | 105      | 384.6                                   | 21.43                                       | <b>11.04%</b> |   |
|              | FIN                     | Finland        | <b>7.09%</b>  | 63       | 88.3                                    | 2.95  | <b>1.52%</b>  |   |
|              | JPN                     | Japan          | <b>5.29%</b>  | 47       | 467.5                                   | 11.66                                       | <b>6.00%</b>  |   |
|              | SGP                     | Singapore      | <b>4.61%</b>  | 41       | 486.8                                   | 10.59                                       | <b>5.45%</b>  |   |
|              | NLD                     | Netherlands    | <b>3.82%</b>  | 34       | 313.0                                   | 5.65  | <b>2.91%</b>  |   |
|              | FRA                     | France         | <b>3.60%</b>  | 32       | 57.2                                    | 0.97  | <b>0.50%</b>  |   |
|              | KOR                     | South Korea    | <b>2.81%</b>  | 25       | 439.5                                   | 5.83  | <b>3.00%</b>  |   |
|              | IRL                     | Ireland        | <b>2.81%</b>  | 25       | 338.0                                   | 4.48  | <b>2.31%</b>  |   |
|              | GBR                     | United Kingdom | <b>2.59%</b>  | 23       | 221.8                                   | 2.71  | <b>1.39%</b>  |   |
|              | CAN                     | Canada         | <b>2.25%</b>  | 20       | 143.0                                   | 1.52  | <b>0.78%</b>  |   |
|              | EST                     | Estonia        | <b>1.24%</b>  | 11       | 433.9                                   | 2.53  | <b>1.30%</b>  |   |
|              | AUS                     | Australia      | <b>1.24%</b>  | 11       | 566.7                                   | 3.31  | <b>1.70%</b>  |   |
|              | HKG                     | Hong Kong      | <b>1.12%</b>  | 10       | 696.0                                   | 3.69  | <b>1.90%</b>  |   |
|              | CHE                     | Switzerland    | <b>0.90%</b>  | 8        | 43.2                                    | 0.18  | <b>0.09%</b>  |   |
|              | Other                   | <b>27.00%</b>  | 240           | 481.0    | 61.26                                   | <b>31.55%</b>                               |               |   |
|              | Total                   | <b>100%</b>    | <b>889</b>    |          | <b>194.18</b>                           | <b>100%</b>                                 |               |   |

Bold values indicate percentage distribution of nodes within the Ripple network by country.



conditions. Each of the six technical and spatial process steps was validated by a corresponding Ethereum transaction, thereby confirming the physical manipulation or movement of each log. It was confirmed that six transactions per log provide a robust and practically sufficient baseline for blockchain-based timber traceability. This baseline can be extended or aggregated depending on regulatory, certification or operational requirements. This empirically grounded transaction model serves as the reference scenario for the subsequent energy, emission and cost analysis of blockchain consensus mechanisms.

Overall, this empirically validated transaction model provides the operational and quantitative foundation for the subsequent assessment of energy consumption, emissions, and costs across different blockchain consensus mechanisms.

## 5 Discussion

While prior research has extensively documented the relative energy efficiency of consensus mechanisms such as Proof-of-Stake



FIGURE 3  
Single log identification, by Lukas Stopfer based on Tracy of Sweden, (2025).

sustainability assessments and their practical application in the context of regulated forestry.

### 5.1 Energy consumption and consensus mechanisms (RQ1)

All energy consumption values reported for RQ1 refer to individual traceability events as defined by the six-event transaction model validated under real forestry conditions. The results confirm that the energy consumption of DLT-based traceability systems varies substantially depending on the consensus mechanism employed. Traditional centralized databases consume negligible energy because validation is performed by a single authority. In contrast, blockchain systems distribute validation across multiple nodes to ensure transparency, immutability and tamper resistance, thereby increasing computational demand. In a DLT-enabled timber traceability framework (Table 12), each of the six defined transaction points represents a cryptographically validated event. As these events occur frequently in operational forestry, energy efficiency is key to determining the technical and environmental feasibility of integrating blockchain technology at scale. The comparative analysis shows that consensus mechanisms affect sustainability by several orders of magnitude. PoW-based systems such as Bitcoin are the most energy- and carbon-intensive, consuming around 6,269 kWh per transaction (an order-of-magnitude estimate based on network-

(PoS), PBFT and Directed Acyclic Graphs (DAG) compared to Proof-of-Work (PoW), this study does not claim to be the first to identify these differences. Rather, the study's contribution lies in operationalizing well-established findings on energy efficiency within a realistic timber supply chain. This is achieved by empirically validating transaction volumes through a real-world pilot and by integrating continuously updated network data to assess sustainability at the level of individual traceability events. By doing so, the study bridges the gap between abstract blockchain

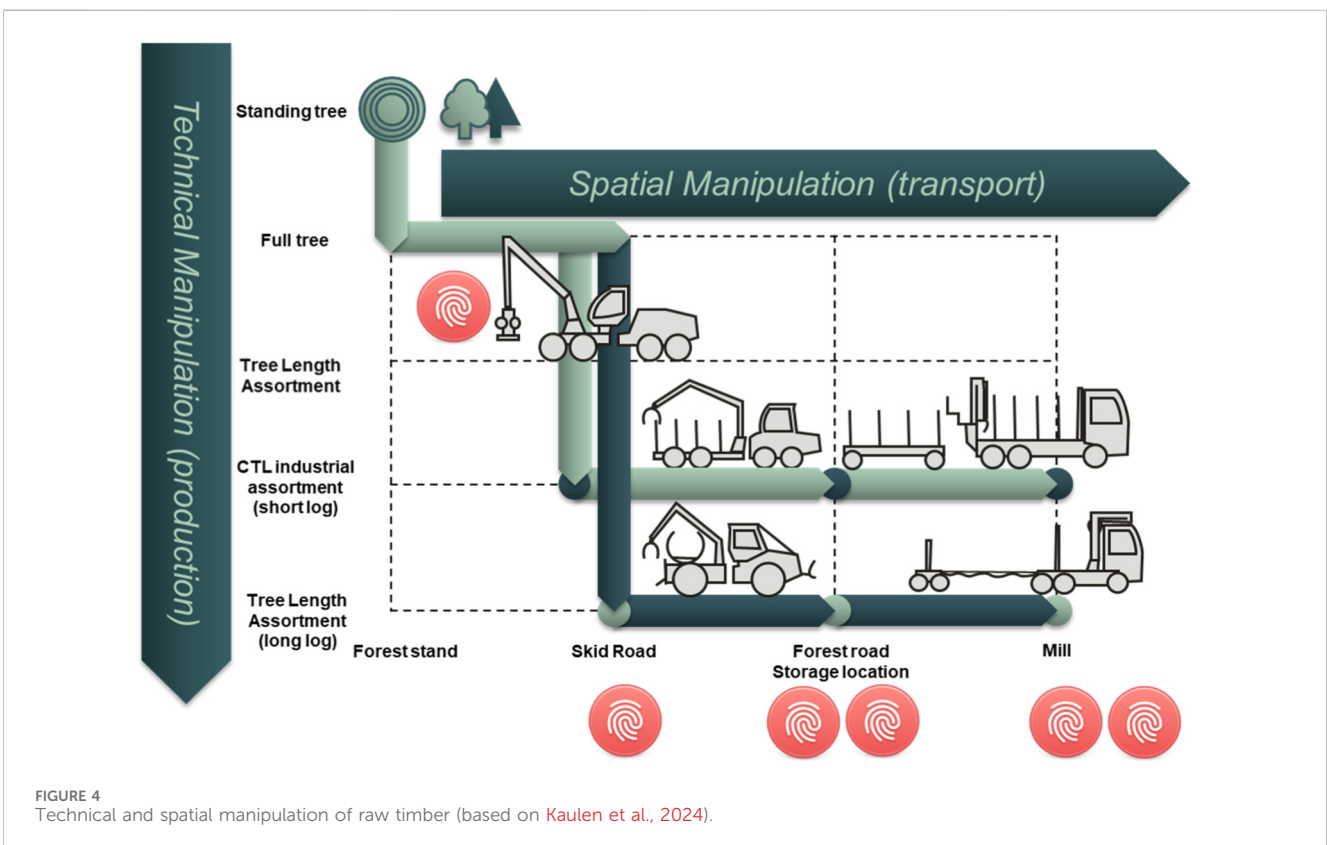


FIGURE 4  
Technical and spatial manipulation of raw timber (based on Kaulen et al., 2024).

TABLE 12 Overview of different blockchain systems by consensus mechanism, power consumption, emission and costs according to a possible timber supply chain with 6 transactions.

| x = 6    | Energy consumption (x) | Emissions (x)            | Price (x) |
|----------|------------------------|--------------------------|-----------|
| System   | kWh/t(x)               | kgCO <sub>2</sub> e/t(x) | \$/t (x)  |
| Bitcoin  | 6269.2                 | 2467.8                   | 6.0720    |
| Ethereum | 0.0485                 | 0.0148                   | 3.3540    |
| Cardano  | 0.0930                 | 0.0319                   | 0.5713    |
| Solana   | 0.0011                 | 0.0019                   | 0.0092    |
| Ripple   | 0.0073                 | 0.0030                   | 0.0051    |
| Iota     | undefined              | 0.0005                   | 0         |

wide averages) and emitting approximately 2.47 tons of CO<sub>2</sub> equivalent per traceability event. Using such a system for all six validation stages would result in prohibitively high energy demand, making PoW unsuitable for industrial timber traceability. In contrast, PoS and hybrid systems, such as those used by Ethereum, Cardano, and Solana, achieve energy reductions of over 99.9% compared to PoW systems, while still providing sufficient security for multi-node validation. PBFT-based systems (e.g., Ripple) and DAG-based architectures (e.g., IOTA) reduce energy consumption further, to below 0.01 kWh per transaction. These findings show that the sustainability of blockchain-based timber tracking depends on the choice of consensus architecture and node distribution, rather than on the use of distributed ledgers *per se*.

### 5.2 Energy emission relationship (RQ2)

The analysis of RQ2 reveals a direct relationship between energy consumption and CO<sub>2</sub> emissions, moderated by the electricity mix of countries hosting validating nodes. This comparison is based on the defined functional unit and the validated transaction granularity, assuming six blockchain-based validation events per cubic meter of roundwood. Proof-of-Work (PoW)-based systems operating in coal-intensive grids produce disproportionately high emissions, whereas proof-of-stake (PoS), PBFT-style and DAG-based systems generate near-zero operational emissions when powered by low-carbon energy sources.

The extent of these differences becomes particularly clear in the context of forestry. As an illustrative example, let us consider a functional unit of traceability of 1 m<sup>3</sup> of round timber assortments (Table 13). About 1 m<sup>3</sup> of hardwood stores approximately 1,000 kg of CO<sub>2</sub>e (depending on species, density and moisture content), while the authentication of the associated traceability events on a Proof-of-Work (PoW) blockchain (depending on the network and the CO<sub>2</sub> footprint generated per transaction) can generate many times this amount of CO<sub>2</sub>e. This comparison emphasizes that PoW-based architectures are difficult to reconcile with climate-friendly forest management and highlights the need for low-energy consensus mechanisms (e.g., PoS, PBFT, DAG) in the development of traceability systems that are aligned with sustainability goals.

TABLE 13 KgCO<sub>2</sub> equivalent of selected tree species (Kaulen et al., 2024).

| Tree Species          | Sequestered kgCO <sub>2</sub> e/m <sup>3</sup> |
|-----------------------|--|
| Fagus sylvatica       | 1,063  |
| Quercus robur         | 1,063  |
| Pinus sylvestris      | 823  |
| Pseudotsuga menziesii | 789  |
| Picea abies           | 722  |

### 5.3 Economic feasibility and coordination efficiency (RQ3)

Within the context of the pilot implementation and the defined transaction model, the results indicate that energy-efficient DLT systems can also improve economic coordination along timber supply chains. Once deployed, smart contracts and automated notarizations reduce the need for manual documentation, lower coordination costs and minimize reliance on repetitive third-party audits. High-performance systems such as Solana and IOTA facilitate low-cost or even free transactions with exceptional scalability, enabling all traceability events to be recorded without placing economic constraints on operational workflows. Although implementing blockchain technology incurs infrastructure and integration costs, these are offset to some extent by improvements in data integrity, fraud prevention and logistical optimization.

### 5.4 Sustainable architectures for timber supply chains (RQ4)

The following assessment of suitable blockchain architectures refers specifically to timber supply chains characterized by frequent validation events, decentralized actors, and regulatory traceability requirements. A comparative analysis has identified PoS-, PBFT- and DAG-based architectures as being the most suitable for sustainable timber supply chains. Proof-of-stake (PoS) systems (e.g., Ethereum and Cardano) offer a balance between decentralization, energy efficiency and smart contract functionality. PBFT-style systems

TABLE 14 Categorization of systems according to different criteria based on the previous section.

| System           | Energy requirement in kWh/tx | CO2 emissions in gCO2e/tx | Transaction speed (TPS) | Cost per transaction in \$/tx |
|------------------|------------------------------|---------------------------|-------------------------|-------------------------------|
| Bitcoin (PoW)    | Very high                    | Very high                 | Very low                | Very high                     |
|                  | 1044.9                       | 411,306.2                 | 7                       | 1.012                         |
| Ethereum (PoS)   | Very low                     | Very low                  | Low                     | Moderate                      |
|                  | 0.0081                       | 2.47                      | 16.5                    | 0.559                         |
| Cardano (PoS)    | Low                          | Very low                  | Very low                | Low                           |
|                  | 0.0155                       | 5.31                      | 5.7                     | 0.095                         |
| Solana (PoH/PoS) | Extremely low                | Extremely low             | Very High               | Extremely low                 |
|                  | 0.0002                       | 0.06                      | 50,000                  | 0.002                         |
| Ripple (PBFT)    | Extremely low                | Extremely low             | High                    | Extremely low                 |
|                  | 0.0012                       | 0.50                      | 1500                    | 0.001                         |
| IOTA (DAG)       | Extremely low                | Extremely low             | Extremely High          | No Costs                      |
|                  | 0.0003                       | 0.08                      | 1000-∞                  | 0                             |

(e.g., Ripple) offer fast finality and reliability in environments where validators can be identified. DAG-based systems (e.g., IOTA) achieve high scalability and generate near-zero emissions, making them particularly well-suited to IoT-enabled forestry applications. By contrast, PoW-based blockchains remain environmentally and economically unsuitable for applications requiring frequent validation across multiple supply chain stages.

Institutional willingness and acceptance are decisive factors for applicability in practice. Forest management is characterized by certification systems and regulatory frameworks, such as the Forest Stewardship Council (FSC), the Programme for the Endorsement of Forest Certification (PEFC) and, increasingly, the EU Deforestation Regulation (EUDR). Recent initiatives such as FSC Trace demonstrate that certification bodies are actively exploring digital, interoperable traceability infrastructures that prioritize data integrity, standardization and verifiability over speculative decentralization (Forest Stewardship Council, 2025; FSC Deutschland, 2025).

The transaction model and pilot project in Germany, Black Forest (May 2024) presented in this study are closely aligned with such initiatives, supporting the following:

- parcel-level geolocation and volume tracking, as required by the EUDR
- immutable documentation, compatible with the FSC and PEFC chain-of-custody principles
- selective data disclosure, through off-chain storage combined with on-chain verification

However, there are still some implementation challenges. Limited connectivity in forest areas necessitates offline data collection and delayed authentication. The cost of infrastructure and onboarding may pose a challenge for small forest owners and contractors. Furthermore, institutional adoption is likely to favor hybrid governance models in which blockchain acts as a neutral authentication layer within existing certification and regulatory systems, rather than as a fully autonomous governance mechanism.

## 5.5 Integration of dynamic data sources (RQ5)

The integration of continuously updated data sources was applied to assess sustainability metrics for the pilot-based transaction model and its associated validation events. The study also shows that incorporating continuously updated non-academic data sources, such as blockchain explorers and real-time energy datasets (at defined access dates), substantially improves the temporal accuracy of sustainability assessments. Although these sources introduce uncertainties relating to transparency and methodological heterogeneity, their systematic validation and aggregation, as applied in this study, enable reproducible and practically relevant benchmarking.

## 5.6 Broader implications for sustainability

Beyond the specific research questions, the findings highlight the broader potential of blockchain technology to advance the sustainable digital transformation of the forest sector. Blockchain-based traceability systems address long-standing deficiencies in conventional chain-of-custody frameworks by enabling immutable, decentralized verification that can be securely shared among stakeholders without intermediaries. This enhances transparency, strengthens consumer trust, and facilitates compliance with emerging legal requirements such as the EU Deforestation Regulation (EUDR).

At the same time, the environmental costs of blockchain implementation must be carefully managed. While PoW-based networks remain environmentally prohibitive, systems based on PoS, PBFT, and DAG architectures offer viable pathways toward climate-smart traceability. When powered by renewable energy and integrated with reliable optical identification and automated data transfer, such systems can provide verifiable transparency with a minimal ecological footprint.

## 5.7 Synthesis

The results confirm that the sustainability and efficiency of blockchain-based timber traceability systems are primarily determined by their technical design, particularly the consensus mechanism. Regarding RQ1–RQ2, energy consumption and CO<sub>2</sub> emissions vary significantly across consensus types: Proof-of-Work (PoW) networks such as Bitcoin are highly inefficient, whereas energy-saving mechanisms such as Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), and Directed Acyclic Graphs (DAG) reduce energy demand and emissions by up to 99.9% relative to PoW systems.

For RQ3, energy-efficient systems also lower coordination and transaction costs through automation, enabling transparent and scalable tracking without compromising performance (Table 14). In relation to RQ4, PoS-, PBFT-style, and DAG-based architectures emerge as the most sustainable and economically viable options for timber supply chains. Finally, RQ5 demonstrates that integrating continuously updated non-academic data improves the precision of sustainability assessments when properly validated. Collectively, these results substantiate the hypothesis that energy-efficient consensus mechanisms can achieve sustainability without compromising economic feasibility. Blockchain technology therefore holds considerable potential in the context of timber supply chains as a foundation for transparent, low-carbon, and trustworthy forest governance. To provide a comparative overview of the findings discussed above, the blockchain systems evaluated in this study were categorized according to their energy consumption, CO<sub>2</sub> emissions, transaction throughput, and cost efficiency. As demonstrated, the energy use and cost performance of blockchain solutions for timber supply chains depend strongly on the underlying consensus mechanism. System architecture further shapes scalability and cost efficiency. Undesirable values are indicated in red, whereas desirable values are shown in green.

## 5.8 Limitations and robustness

This study partly relies on continuously updated non-academic data sources, such as blockchain explorers and sustainability monitoring platforms. These sources are not peer-reviewed and may change over time. Consequently, absolute numerical values for energy consumption, emissions, and transaction costs are time-specific estimates rather than fixed constants. To mitigate this, all data were collected on clearly documented dates, cross-validated using multiple independent sources and aggregated using transparent procedures. The full calculation workflow and all source references are provided in the Supplementary Material to ensure reproducibility (Stopfer and Buss, 2025).

Despite these limitations, the robustness of the results lies in the consistency of the relative differences between consensus mechanisms across all data sources. Although absolute values may vary, the order-of-magnitude contrasts between Proof-of-Work, Proof-of-Stake, PBFT and DAG-based systems remain stable and are strongly supported by peer-reviewed literature. Consequently, the study's conclusions regarding the suitability of low-energy consensus mechanisms for sustainable timber

traceability remain robust despite data uncertainty, although precise numerical estimates may change as networks and measurement methodologies evolve.

## 6 Conclusion

All quantitative results presented in this study should be interpreted in the context of the defined six-event transaction model, the pilot implementation in the Black Forest, and the domain-specific assumptions of forestry supply chains. This study examined the energy consumption, CO<sub>2</sub> emissions and transaction efficiency of various blockchain consensus mechanisms, focusing specifically on their potential application in timber supply chains. The findings show that the energy demand and environmental impact of blockchain vary substantially depending on the type of network and the consensus mechanism used. Proof-of-Work (PoW) systems such as Bitcoin remain highly energy-intensive and environmentally unsustainable. In contrast, Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), Proof-of-History (PoS and PoH) and Directed Acyclic Graph (DAG) architectures offer significantly improved scalability, efficiency and sustainability. PoS-based mechanisms, as implemented in Ethereum 2.0 and Cardano, reduce energy consumption by up to 99.9% compared to PoW. Furthermore, newer systems such as Solana and IOTA demonstrate that near-zero emissions and low transaction costs can be achieved without compromising performance. These energy-efficient blockchain models therefore represent viable solutions for traceability and transparency within the timber sector, where ecological considerations are increasingly important. The results also reveal a direct correlation between CO<sub>2</sub> emissions and the electricity mix of the host country, highlighting the importance of integrating renewable energy and location-specific deployment strategies when implementing DLT systems. While blockchain technologies may entail higher initial energy costs from an economic standpoint, the long-term benefits such as improved traceability, reduced illegal logging, and enhanced trust in sustainable wood products can outweigh these drawbacks. This research supports the adoption of energy-efficient, low-cost blockchain architectures for sustainable timber supply chains. Future work should focus on quantifying the net environmental and social benefits of blockchain deployment, refining emission models using continuously updated real-world data and developing standardized sustainability assessment frameworks for distributed ledger systems.

## Data availability statement

Replication Materials: Energy Consumption Timber Blockchain available from: <https://osf.io/exq25/overview>.

## Author contributions

LS: Conceptualization, Methodology, Formal Analysis, Writing – original draft, Writing – review and editing, Project administration. EB: Writing – original draft, Writing – review

and editing. AK: Writing – original draft. FB: Writing – original draft. FDM: Validation, Investigation, Writing – review and editing. MP: Writing – review and editing. SL: Writing – review and editing. ME: Writing – original draft. SB: Writing – review and editing. MH: Conceptualization, Writing – review and editing. TP: Conceptualization, Funding acquisition, Resources, Writing – review and editing.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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