effectively, but whether better monitoring will translate into better outcomes. The history of environmental science is littered with meticulously documented declines. AI's most important contribution to conservation may not be its ability to detect change, but its potential to predict it—to shift the paradigm from documenting what has already been lost to anticipating and preventing harm before it occurs. Realizing that potential will require not only continued technical innovation but sustained attention to the ethical, political, and structural dimensions of the biodiversity crisis. The machines are learning to see the natural world with unprecedented clarity. Whether we act on what they reveal remains a fundamentally human choice.

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THE ENVIRONMENTAL FOOTPRINT OF BLOCKCHAIN: HOW THE

TRANSITION TO PROOF-OF-STAKE IS SHAPING THE GREEN FUTURE

Chekalov I. student,
T. Gerasymchuk, Ph.D, Associate professor,
Kharkiv National Automobile and Highway University

Blockchain technology has long been celebrated as a revolutionary force for decentralization, but its environmental toll has become a defining issue for the industry. The energy-intensive process of validating transactions on early networks has drawn sharp criticism from environmental advocates, regulators, and institutional investors alike. However, a fundamental shift is now underway. The transition from Proof-of-Work (PoW) to Proof-of-Stake (PoS) consensus mechanisms is dramatically reshaping the ecological footprint of digital assets, with Ethereum's landmark "Merge" setting a precedent that is reverberating across the entire crypto ecosystem. This article examines the scale of blockchain's environmental challenge, the mechanics and impact of the PoS transition, and the emerging regulatory and market forces that are steering the industry toward a more sustainable future.

The Environmental Burden of Proof-of-Work For over a decade, the dominant method for securing blockchain networks relied on the brute computational force of Proof-of-Work mining. In this system, miners compete to solve complex cryptographic puzzles, with the winner earning the right to validate the next block of transactions and receive newly minted coins. The deliberate design choice—requiring ever-increasing computational power as more miners join the network—has turned Bitcoin mining into an industrial-scale energy operation. Bitcoin's annual electricity consumption is estimated at approximately 138 TWh, with associated emissions of around 39.8 Mt CO_2 equivalent (de Vries, 2023). Other estimates place the figure as high as 173 TWh annually, roughly 0.5% of global electricity production, comparable to the entire consumption of countries like Poland or the Netherlands (Cambridge Centre for Alternative Finance, 2025). The same report indicates that approximately 52.4% of Bitcoin's energy now comes from sustainable sources, a notable increase from 37.6% in 2022, though this still leaves a substantial fossil-fuel component in its energy mix (Cambridge Centre for Alternative Finance, 2025).

Beyond direct energy consumption, PoW mining generates significant electronic waste. The specialized ASIC (Application-Specific Integrated Circuit) hardware used for Bitcoin mining has a notoriously short operational lifespan of approximately one to two years before becoming obsolete. This rapid turnover creates a continuous cycle of hardware replacement, with estimates suggesting that mining a single Bitcoin produces between 272 and 400 grams of electronic waste (de Vries & Stoll, 2021). However, there is emerging debate about the accuracy of these figures, with some researchers arguing that ASICs remain profitable for much longer than previously assumed, and that strong economic incentives drive recycling and reuse within the mining industry (Mining Hardware Lifecycle Consortium, 2025). ASIC refurbishing has emerged as a technical discipline that extends hardware lifecycles, reduces e-waste, and supports network decentralization by lowering the cost of entry for smaller miners.

The Proof-of-Stake Revolution Proof-of-Stake fundamentally reimagines how blockchain networks achieve consensus. Rather than requiring validators to expend energy through computation, PoS selects validators based on the amount of cryptocurrency they "stake" or lock up as collateral. This eliminates the energy arms race that defines PoW mining, slashing electricity consumption to a fraction of its former levels. A systematic literature review of eight major consensus mechanisms published in 2025 found that energy-efficient alternatives like PoS and Directed Acyclic Graphs can reduce energy use by over 99% compared to PoW, though trade-offs in decentralization and security persist (Gupta et al., 2025). Simulation-based comparisons consistently demonstrate that PoS consumes considerably less energy and enables quicker transaction confirmations while preserving similar levels of network stability (Wang et al., 2025).

The transformative potential of PoS is best illustrated by Ethereum's historic Merge on September 15, 2022. Ethereum's transition from PoW to PoS resulted in a staggering 99.95% reduction in the network's energy consumption (CCRI, 2022). Prior to the Merge, Ethereum's annual energy consumption ranged from 46.31 to 93.98 TWh, comparable to the energy usage of a small country like Hong Kong or Chile. After the upgrade, Ethereum's energy use plummeted to approximately 0.01 TWh, a level comparable to the annual electricity consumption of roughly 100 average U.S. homes (Digiconomist, 2023). According to the Crypto Carbon Ratings Institute (CCRI), this translated to a 99.99% reduction in carbon emissions, with annual CO_2 output falling from over 11 million tons to approximately 870 tons (CCRI, 2022). As Viraj Nair, Lecturer in Fintech at the University of East London, observed in a 2026 comparative study published in the Journal of Enterprise Information Management, "The energy intensity of earlier blockchain systems has become a major barrier to wider adoption. The findings show that newer approaches offer a viable path to reducing blockchain's environmental footprint" (Nair, 2026, p. 462).

The Merge has also had measurable effects on Ethereum's market position. An ESG Benchmark developed in collaboration with CCRI showed Ethereum's environmental score improving from 10.7 to 26.0 immediately after the Merge, propelling the network from sixth to first place in overall ESG ranking—a position it has maintained since late 2022 (CCRI & South Pole, 2022). This improvement has attracted institutional investors who were previously constrained by environmental, social, and governance (ESG) mandates, with over one million active validators now securing the network through more than 36 million staked ETH, nearly a third of the total supply (Ethereum Foundation, 2025).

Beyond Ethereum: The Broader Green Transition While Ethereum's Merge represents the most prominent case study, other blockchain networks are also demonstrating that sustainability and functionality are not mutually exclusive. The XRP Ledger, which uses a consensus protocol distinct from both PoW and PoS, records annual carbon emissions of just 63 metric tons of CO_2 equivalent—roughly the footprint of a single transatlantic flight—with each transaction producing only

8.1 milligrams of CO_2 (Ripple, 2023). Cardano, which has operated on a PoS-based Ouroboros protocol since its inception, was designed specifically to avoid the environmental pitfalls of PoW and has maintained a consistently low energy profile throughout its operational life (IOHK, 2022).

The regulatory environment is also accelerating this transition. The European Union's Markets in Crypto-Assets Regulation (MiCA), which took full effect in 2025, mandates that crypto-asset service providers disclose detailed information on the environmental and climate impacts of the assets they offer, including energy consumption and carbon emissions, in their white papers (Regulation (EU) 2023/1114). The EU Commission's Delegated Regulation (EU) 2025/422 establishes concrete requirements for climate and environmental data disclosure for crypto-asset service providers whose energy consumption exceeds defined thresholds (European Commission, 2025). This regulatory push has created a compliance infrastructure that incentivizes the adoption of energy-efficient consensus mechanisms. As Nair emphasized, "Improving energy efficiency will be critical as blockchain technologies expand into enterprise and public sector use, where environmental considerations are shaping investment and regulatory decisions. Lower-energy systems represent a more sustainable foundation for future blockchain technologies" (Nair, 2026, p. 473).

The Crypto Climate Accord, inspired by the Paris Climate Agreement, has set a target for the crypto industry to achieve net-zero emissions from electricity consumption by 2030 (Crypto Climate Accord, 2021). This industry-led initiative, combined with regulatory frameworks like MiCA and the growing prominence of ESG criteria in institutional investment decisions, means that blockchain projects with poor sustainability performance face not only reputational damage but also higher costs of capital and reduced market access. Research indicates that if the crypto industry fails to make substantial progress on energy sustainability, it risks losing access to institutional funds that are increasingly tied to ESG compliance (OECD, 2024).

Persistent Challenges and Critiques Despite these impressive gains, the green transition in blockchain is not without its complications. PoS systems introduce governance trade-offs that warrant careful consideration. Research on Ethereum's transition notes risks of validator concentration, where a small number of large staking entities could potentially exert disproportionate influence over the network, as well as concerns about delegator passivity in governance participation (Wan et al., 2023). The systematic review published in 2025 similarly cautions that while PoS and other energy-efficient mechanisms dramatically reduce energy consumption, "trade-offs in decentralization and security remain" (Gupta et al., 2025, p. 15). The energy efficiency gains of PoS may also introduce participation inequalities if staking requirements—which typically demand a minimum of 32 ETH for solo validation on Ethereum—favor wealthier actors. Simulation-based comparisons of five major consensus mechanisms confirm that while PoS balances energy efficiency with moderate decentralization, Delegated Proof-of-Stake (DPoS) achieves greater scalability at the expense of decentralization (Wang et al., 2025).

Furthermore, the PoW ecosystem has not stood still. Bitcoin mining's shift toward renewable energy—now at 52.4% sustainable according to Cambridge data—complicates the narrative that PoW is inherently unsustainable (Cambridge Centre for Alternative Finance, 2025). Some researchers argue that Bitcoin mining, when integrated with regenerative energy concepts and flexible load management, can make a positive contribution to climate protection by providing demand response services that support grid stability and renewable energy deployment (Müller et al., 2024). The development of more energy-efficient ASIC hardware has also reduced the electricity required per hash computation. The International Monetary Fund has proposed a carbon tax on crypto miners that could generate an estimated $5 billion annually in revenue while incentivizing further shifts toward clean energy (IMF, 2024). Additionally, the emerging discipline of ASIC refurbishing challenges assumptions about mining e-waste, demonstrating that so-called obsolete hardware retains significant value and can extend operational lifecycles when properly maintained (Mining Hardware Lifecycle Consortium, 2025).

Conclusion The environmental footprint of blockchain technology has undergone a remarkable transformation, with the transition from Proof-of-Work to Proof-of-Stake representing the single most significant sustainability intervention in the industry's history. Ethereum's 99.95% reduction in energy consumption following the Merge, now validated by three years of post-transition data, provides a powerful proof-of-concept that energy-intensive consensus mechanisms are a design choice rather than an inevitability. As the systematic literature review concludes, blockchain can "support global sustainability goals through the integration of energy-efficient consensus models, policy compliance, and future innovations" (Gupta et al., 2025, p. 21).

Yet the journey toward a truly green blockchain ecosystem remains incomplete. The environmental burden of Bitcoin—which continues to operate on PoW at national-scale energy consumption levels—demonstrates that technological solutions alone cannot resolve the tension between decentralization and sustainability without accompanying regulatory and market pressure. The MiCA framework in Europe, the Crypto Climate Accord, and the growing influence of ESG-conscious institutional capital are creating powerful incentives for the broader adoption of energy-efficient consensus mechanisms. As the comparative research by Nair affirms, while Proof-of-Stake delivers substantial sustainability and scalability advantages over Proof-of-Work, "its long-term effectiveness depends on governance mechanisms capable of preserving decentralisation and accountability" (Nair, 2026, p. 476). The green blockchain of the future will need to be not only energy-efficient but equitably governed—a challenge that will define the next phase of the industry's evolution.

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GREEN LOGISTICS: REDUCING CARBON FOOTPRINT IN SUPPLY CHAIN OPERATIONS

R. Togayev, student,
Kharkiv National Automobile and Highway University

The global logistics sector is the circulatory system of modern commerce, but it is also a major contributor to the climate crisis. Freight transport alone accounts for approximately 8% of global CO_2 emissions, a figure that rises to over 10% when warehousing, packaging, and logistics facilities are included (International Energy Agency [IEA], 2023). With international freight volumes projected to triple by 2050 under business-as-usual scenarios, the urgency to decouple logistics growth from emissions growth has never been greater (International Transport Forum [ITF], 2023). Green logistics—the systematic effort to measure, minimize, and mitigate the environmental impact of logistics operations—has evolved from a niche corporate social responsibility concern into a strategic imperative driven by regulation, investor pressure, and fundamental economic logic.

The Carbon Footprint of Logistics: Understanding the Baseline The logistics carbon footprint is concentrated in transportation. Heavy-duty trucks, which represent only 4% of the global vehicle fleet, are responsible for roughly 40% of