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BRIDGING THE ACCOUNTABILITY GAP THROUGH SMART CONTRACT DRIVEN CARBON OFFSETTING AND DIGITAL ASSET RECOGNITION IN THE METAVERSE

METAVERSE'DE AKILLI SÖZLEŞME TABANLI KARBON DENGELEME VE DİJİTAL VARLIK TANIMA YÖNTEMLERİYLE HESAP VERİLEBİLİRLİK AÇIĞINI KAPATMAK

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ABSTRACT

The rapid evolution of the metaverse presents a profound normative dilemma regarding its ecological legitimacy. This study addresses the "accountability gap" inherent in decentralized ecosystems, where the fragmented identity of the polluter complicates the enforcement of the 'polluter pays' principle and the state's constitutional obligation to protect the environment. To mitigate these challenges, this study proposes an original net emission balance model Enet as a conceptual and regulatory tool to quantify the net climate impact of metaverse operations. The framework integrates blockchain-based green oracles and smart contracts to facilitate real-time, tamper-proof carbon tracking and automated offsetting. At the core of these solutions is recognizing tokenized carbon credits as property-law-based digital assets, aligning environmental compliance with secure digital ownership. Furthermore, this study advocates for a shift toward 'hard law' requirements through mandatory emission licensing, targeted fiscal instruments, such as deterrent taxes on energy-intensive Proof of Work (PoW) protocols and legally guaranteed cross-platform interoperability to prevent digital lock-in and regulatory arbitrage.

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ÖZ

Metaverse'ün hızlı gelişimi, ekolojik meşruiyetine ilişkin derin bir normatif ikilem ortaya çıkarmaktadır. Bu çalışma, kirletenin parçalı kimliğinin "kirleten öder" ilkesinin ve devletin çevreyi korumaya yönelik anayasal yükümlülüğünün uygulanmasını güçleştirdiği merkeziyetsiz ekosistemlerdeki hesap verebilirlik boşluğu sorununu ele almaktadır. Bu zorlukların giderilmesi amacıyla çalışma, metaverse faaliyetlerinin net iklim etkisini ölçmeye yönelik kavramsal ve düzenleyici bir araç olarak özgün bir net emisyon dengesi modeli (Enet) önermektedir. Önerilen çerçeve, gerçek zamanlı, değiştirilemez karbon takibini ve otomatik denkleştirmeyi sağlamak amacıyla blokzincir tabanlı yeşil orakılları ve akıllı sözleşmeleri bütünleştirmektedir. Bu çözümlerin merkezinde, tokenleştirilmiş karbon kredilerinin mülkiyet hukukuna dayalı dijital varlıklar olarak tanınması yer almakta; böylece çevresel uyumluluk güvenli dijital mülkiyet ile uyumlu hâle getirilmektedir. Ayrıca çalışma, zorunlu emisyon lisanslaması, enerji yoğun iş ispatı protokollerine yönelik caydırıcı vergiler gibi hedefe yönelik mali araçlar ve dijital kilitlenme ile düzenleyici arbitrajı önlemek amacıyla hukuken güvence altına alınmış platformlar arası birlikte çalışabilirlik yoluyla 'sert hukuk' temelli tedbirlere geçişi savunmaktadır.

Keywords: metaverse, blockchain, carbon management, smart contracts, ecological sustainability.

Anahtar Kelimeler: metaverse, blokzincir, karbon yönetimi, akıllı sözleşmeler, ekolojik sürdürülebilirlik.

INTRODUCTION

The rapid emergence of the metaverse has raised urgent questions regarding its ecological legitimacy. While the metaverse offers transformative opportunities to decouple economic activity from physical resource consumption through virtualization, it simultaneously presents a profound normative dilemma. The core of this dilemma resides in the tension between the state's constitutional obligation to protect the environment and nascent digital property rights within decentralized ecosystems (Alzoubi & Mishra, 2023: 8; De Giovanni, 2023; Rathnayake et al., 2025: 214-217). A critical concern within this discourse is the environmental footprint of blockchain protocols, particularly those utilizing energy-intensive PoW consensus mechanisms. Such architectures pose a direct threat to ecological sustainability; for instance, a single Non-fungible Token (NFT) transaction can generate up to 150 kg CO2 emissions, while the annual energy consumption of the Bitcoin network rivals that of mid-sized nation-states (De Giovanni, 2023; Sadawi et al., 2021). However, the recent paradigmatic shift toward Proof of Stake (PoS) protocols has demonstrated a potential reduction in energy expenditure by over 99%. This evolution positions blockchain as a central pillar for carbon management solutions, enabling transparent tracking, decentralized carbon markets and automated regulatory compliance. High-fidelity simulations and optimization models increasingly validate the efficacy of blockchain frameworks in enhancing carbon policy (Lanteri et al., 2025). From a legal perspective, this high-energy demand creates an accountability gap: in a decentralized environment, the traditional polluter identity becomes fragmented between platform operators, smart contract developers and users. Without a clear definition of the legal subject of environmental liability, the "polluter pays" principle remains unenforceable in virtual spaces.

The inherent characteristics of blockchain facilitate the construction of robust systems for carbon credit trading, emission monitoring and supply chain accountability. Peer-to-peer (P2P) trading frameworks further empower 'prosumers' to engage directly in energy and carbon allowance exchanges through transparent, incentive-based pricing models. Smart contracts are central to this operational efficiency, as they automate the verification and enforcement of emission thresholds and offsetting protocols (Vladucu et al., 2024: 343). Current scholarship emphasizes that the integration of blockchain-based carbon management into metaverse architecture offers both substantial risks and transformative potential. Secure data management and real-time monitoring capabilities form the foundation of carbon accounting systems that align with the United Nations Sustainable Development Goals (SDGs) and global climate mandates (De Giovanni, 2023; Sadawi et al., 2021). However, the literature underscores that addressing digital equity, environmental justice and cross-border regulatory compliance requires a multi-stakeholder governance approach involving policymakers, technologists and civil society (Mulligan et al., 2023: 11).

As the metaverse transitions from a conceptual framework to a pervasive reality, the establishment of a comprehensive blockchain-based carbon management and regulatory framework is imperative to ensure that digital growth does not exacerbate existing environmental crises. This review synthesizes contemporary research on these frameworks, evaluating their effectiveness for policymakers while highlighting the persistent challenges of rebound effects such as e-waste and social inequality. Ultimately, the efficacy of these digital tools remains contingent upon strategic protocol selection, integration with renewable energy infrastructures and the standardization of reporting practices across jurisdictions. Realizing this potential necessitates informed policy interventions, including explicit legal recognition of digital assets, enforceable transparency standards and the promotion of platform interoperability (Çolak and Sandalcılar, 2019: 205-232; Karim et al., 2023: 7-15). This article proposes an original net emission balance model as a normative basis for this framework, ensuring that the metaverse evolves as a sustainable ecosystem grounded in constitutional and international legal principles.

Current literature addresses the problem of the metaverse's ecological legitimacy across three distinct and largely disconnected axes. The technical blockchain-carbon governance literature evaluates the monitoring performance of oracle architecture and smart contracts from an engineering perspective. The literature measuring the metaverse's ecological footprint descriptively quantifies the emission savings of virtual events through life-cycle assessment methodologies, while the tokenization law literature discusses the status of tokenized carbon credits under property law at a general level. Conversely, debates on the duty of care within information technology law remain exclusively centered on data privacy and cybersecurity, completely excluding environmental externalities. Although contemporary academic trends fragmentarily address the risks of the metaverse toward fundamental rights and general environmental, social and governance (ESG) reporting, or consumer law gaps in decentralized spaces, none of these categories propose a holistic model that integrates technical measurement data, the constitutional right to the environment, and digital property law within the same regulatory framework. The literature quantifies emissions, legally classifies tokens or technically validates oracle architectures; however, it fails to present a normative synthesis capable of transforming these elements into an applicable bridge between "code" and "law". By transcending this fragmented structure, this study fills this multidisciplinary gap in the literature by proposing a holistic techno-legal framework that merges the accountability principle based on constitutional environmental law with blockchain-based technical verification mechanisms (E_{net} model) and digital property law.

1. THE ECOLOGICAL RESPONSIBILITY OF DIGITALIZATION: CONSTITUTIONAL AND INTERNATIONAL LEGAL BASES

The paradigm shift driven by global digitalization necessitates a foundational reassessment of traditional legal regimes, forcing a convergence between information technology law and environmental jurisprudence. As decentralized ecosystems, advanced data processing paradigms, and immersive virtual environments expand exponentially, their physical resource dependencies and systemic carbon footprints present unprecedented challenges to contemporary governance models. This socio-technical evolution creates an imperative to establish a rigorous legal taxonomy that internalizes the ecological externalities of digital infrastructures. Resolving this tension requires a multi-layered normative inquiry that bridges national constitutional imperatives with the evolving instruments of the international climate acquis.

1.1. Constitutional Basis

The environmental right to live in a healthy environment, as enshrined in many constitutions, imposes a state duty to protect the environment that can extend to digital platform operators through an environmental duty of care. This concept necessitates integrating an ecological responsibility dimension into the information technology law framework to ensure sustainable digital ecosystem governance. Within the Turkish constitutional framework, this aligns precisely with Article 56 of the Constitution of the Republic of Türkiye, which guarantees everyone the right to live in a healthy and balanced environment and charges both the state and citizens with the duty to improve and protect it (Constitution of the Republic of Türkiye, 1982, Art. 56.). Consequently, this constitutional mandate provides a robust legal foundation for extending ecological obligations to digital platform operators acting within Turkish jurisdiction. The state's duty of care mandates that digital platforms, pivotal actors in modern information dissemination and economic activity, adhere to environmental norms that prevent ecological harm and promote green innovation. This is consistent with broader regulatory trends aimed at enhancing platform accountability, transparency and social responsibility, as illustrated by the European Union's Digital Services Act (DSA), which increases platform obligations regarding content moderation and transparency (Kaushal et al., 2024). Specifically, environmental regulations spur corporate environmental responsibility, which in turn fosters green technology innovation and sustainability practices within enterprises, emphasizing how regulatory frameworks can leverage platform responsibilities to create positive ecological outcomes. Incorporating an ecological responsibility layer into information technology law aligns with governance strategies that harmonize technology development with environmental sustainability, requiring mechanisms for environmental impact monitoring, transparency and accountability, similar to those in emerging digital regulatory frameworks globally (Turillazzi et al., 2023: 84).Such ecological duties could manifest as mandatory platform disclosures on energy consumption, supply chain environmental impacts, or obligations to adopt green technologies, harmonizing with cross-sector regulatory architectures that support scalable compliance in multi-industry contexts, including digital services (Cadet et al., 2024: 496). This responds to the constitutional and societal imperatives of environmental protection by embedding sustainability within the operational and legal responsibilities of digital platform operators.

Thus, to actualize this 'environmental duty of care', information technology law acquis must evolve beyond current norms focused primarily on data privacy and content regulation to embrace binding ecological responsibilities. This would support constitutional rights to a healthy environment, ensuring that digital platforms contribute positively to environmental stewardship while aligning with ethical, legal and professional standards of care prevalent in other regulated sectors (Dowie, 2017: 48-50).

1.2. International Acquis

Mandatory reporting of the carbon costs of digital services is gaining attention within the framework of several major international and European climate and sustainability policies and agreements. The Corporate Sustainability Reporting Directive (CSRD), rooted in the European Green Deal's climate action objectives, mandates large and listed companies to disclose information on social and environmental risks, opportunities and impacts, which logically extends to carbon emissions related to digital services (Poulle et al., 2024: 648-650). This directive aims to enhance transparency and integrate ESG factors into corporate strategies as a strategic imperative, fostering stakeholder trust and aligning companies with sustainable operations goals (Fornasari and Traversi, 2024: 117). The CSRD's gradual applicability through 2024 to 2029 signals a growing regulatory requirement for comprehensive environmental reporting, possibly including digital carbon footprints. Internationally, the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement frame global climate governance around mitigating greenhouse gas emissions with a system based on nationally determined contributions (NDCs) and a 'pledge and review' mechanism (Kuyper et al., 2018: 348). While these agreements focus on broad country-level commitments, the Paris Agreement's architecture also supports efforts to integrate sectoral emissions, such as those from digital services, into mitigation policies by increasing transparency and accountability. The UNFCCC's evolving frameworks and learning mechanisms encourage countries and actors to adopt low-carbon economic transitions, which implicitly cover digital economy sectors (Rietig, 2019). The European Climate Agreement and the Green Deal set ambitious European Union (EU) wide environmental and climate goals, aiming for climate neutrality by 2050. These frameworks support regulations such as the DSA, which governs digital service providers and could evolve to include sustainability and carbon cost transparency requirements, merging digital policy with environmental objectives. Moreover, the high-level commission on carbon prices reflects an economic approach to incentivize climate action through pricing mechanisms that could influence accounting for carbon costs in digital services and encourage efficient and sustainable practices (Veral, 2022: 120; Stern and Stiglitz, 2017: 24).

Collectively, these policies and agreements drive the momentum toward mandatory reporting of carbon costs in digital services by enhancing regulatory demands for environmental impact disclosure, fostering international cooperation and benchmarking and incentivizing the reduction of carbon footprint in the digital sector. This aligns with the broader ambition of decarbonizing economies and integrating sustainability into all business operations, including the growing digital infrastructure and services domain.

1.3. Legal Gap and Conflict of Rights

The current regulatory landscape concerning digital technologies primarily emphasizes data privacy and cybersecurity protections, creating a significant legal gap regarding the physical carbon costs of technology production, deployment and use. This gap exists because existing laws and regulations predominantly address intangible digital rights, such as data ownership, confidentiality and protection against cyber threats, rather than environmental externalities, such as carbon emissions tied to digital services and infrastructure (Watini et al., 2024: 29). The principle of proportionality plays a pivotal role in reconciling conflicts between individual digital property rights, such as the right of users to access and control personal data and the collective right to a healthy and sustainable environment. In this context, proportionality mandates that digital rights should be exercised within limits that do not disproportionately harm environmental interests, ensuring that personal or corporate digital freedoms do not undermine public health or climate goals. Hence, balancing these rights involves evaluating the extent of users or providers digital entitlements against the environmental harm caused by the carbon footprint of digital services and technology infrastructure. However, this balance is complicated by the absence of explicit legal provisions addressing the environmental footprint within data privacy or cybersecurity laws. While multiple jurisdictions have robust legal frameworks to protect privacy, secure data and manage cyber risks, these typically do not incorporate environmental accountability for the carbon costs of digital activities. This legal vacuum highlights the need for adaptive legal approaches that integrate environmental considerations into digital governance. Such frameworks would require expanding existing digital rights laws or climate regulations to encompass mandatory reporting and mitigation of the carbon impact of digital services and infrastructure. Moreover, legal scholars have advocated for reforms that bridge cybersecurity, privacy and environmental law through interdisciplinary mechanisms that respect digital individual rights while safeguarding collective ecological well-being (Prastyanti and Sharma, 2024: 370).

In summary, the principle of proportionality emerges as a critical legal doctrine that mediates the tension between user's digital property rights and society's environmental rights, suggesting that future regulatory developments must incorporate carbon accountability into the digital rights paradigm to effectively address this substantive legal gap.

2. CONCEPTUAL FRAMEWORK AND TECHNICAL BACKGROUND

The digital carbon footprint refers to the aggregate greenhouse gas emissions generated by all the computational processes required to execute a digital activity, such as a virtual meeting within the metaverse (Magaletti et al., 2025) Metaverse platforms exhibit a multi-layered emission architecture encompassing hardware utilization, network traffic, and server-side processing.

Specifically, hardware components, including virtual reality (VR) and augmented reality (AR) devices and user terminals, account for significant energy consumption. Furthermore, network traffic associated with high-bandwidth data transmission further escalates energy demands. Cloud and data center operations represent a substantial contribution to total emissions. Life cycle assessments (LCA) emphasize that accurate carbon accounting must incorporate both direct emissions, such as those from devices and servers, and indirect emissions inherent in the supply chain (Baklaga, 2024: 111).

2.1. Blockchain and Green Oracles: Immortal Evidence System

A blockchain provides an immutable ledger for recording environmental data. Internet of Things (IoT) sensors or smart meters feed real-time energy/emission data into a blockchain. These tools can be conceptualized as 'green oracles' within a blockchain-based carbon governance framework. Green oracle is a secure digital bridge or data transfer mechanism that automatically collects real-time environmental and emission data from physical devices such as IoT sensors, smart meters and carbon tracking devices and transfers it to a blockchain network. This creates an 'immortal evidence system' sealing environmental declarations against tampering or fraud. Such systems are being piloted in supply chains, construction material certification, energy markets, and urban infrastructure (Köse &Polat, 2021: 14-18; Ojadi et al., 2025: 90). Green oracles can improve data reliability by automatically aggregating and transmitting real-time environmental metrics. Systems that connect IoT meters, carbon trackers, and other sensors to a blockchain significantly reduce manual entry and associated errors and increase the granularity of carbon data. One enterprise study reported a 25% improvement in carbon reporting accuracy when IoT meters streamed data into a blockchain-based system (Zhang, 2025). Oil-sector simulations using IoT and blockchain showed traceability accuracy rising from 65/100 to 96/100 (Almher et al., 2025: 591). The immutability of a blockchain means that once oracle-fed data are recorded, they cannot be altered without detection, addressing manipulation, corruption, and opaque adjustments common in traditional carbon accounting. Consensus and multi-party validation of incoming records further enhance data veracity compared with centralized systems (Rodrigo et al., 2020). Green oracle-based systems enable tracing emissions across supply chains and product lifecycles, improving the completeness and consistency of footprints (Rathnayake et al., 2025: 214-217). However, the full assurance of accuracy depends on the quality and calibration of the sensors and measurement devices supplying data to the green oracle, the correctness of the emission factors applied, the reliability of the off-chain models used, and the robustness of the oracle design in preventing incorrect data inputs and their irreversible storage on the blockchain (Ojadi et al., 2025: 93).

In conclusion, blockchain oracles enhance the practical accuracy, reliability, and auditability of carbon footprint data by automating trusted data flows and preventing post-hoc manipulation; however, they must be complemented by high-quality measurement systems and robust verification mechanisms at the oracle boundary.

2.2. Smart Contracts for Real-Time Carbon Credit Offsetting

Smart contracts function as the primary administrative and enforcement layer of the proposed model by automating critical regulatory processes. Utilizing code structures that operate in real-time, these contracts calculate energy-related emissions based on immutable data provided by green oracles. This technical framework ensures that carbon footprints are instantaneously matched with tokenized carbon credits, which are then automatically retired or offset through embedded smart contract logic. To bridge the gap between "code" and "law" this framework ensures that digital obligations are legally enforceable and brought into compliance with existing regulatory oversight (Gitmez, 2025: 226; Sadawi et al., 2021). Smart contracts automate the core components of blockchain-based carbon governance systems. Through emission calculation modules, coded algorithms process real-time data supplied by green oracles to determine the precise carbon footprint of a given activity. These calculated emissions are then programmatically matched with tokenized carbon credits, which can be automatically retired or offset through predefined smart contract logic, ensuring immediate and verifiable compliance. In more advanced regulatory models, smart contract architectures are designed to incorporate legal principles, such as concepts derived from debt law, to strengthen the enforceability of carbon-related obligations, thereby bridging technical automation with legally binding accountability (Patro et al., 2025: 8262).

The literature review strongly supports the proposed conceptual framework by demonstrating that digital carbon footprints in metaverse-like environments, although technically complex, are measurable and quantifiable through adequate instrumentation and lifecycle-based accounting methods (Hong & Xiao, 2024: 3). Blockchain technology contributes to the trustworthiness of environmental reporting through its immutability, while so-called green oracles function as critical bridges between physical emission measurements and digital ledgers, thereby reducing the risks of greenwashing and double-counting. Furthermore, smart contracts facilitate automated carbon offsetting by directly linking verified emission data to tokenized carbon credits, streamlining regulatory compliance, and lowering administrative burdens. Nevertheless, significant challenges persist, including interoperability between platforms, privacy concerns associated with granular data tracking, blockchain scalability–particularly in energy-intensive PoW systems–regulatory harmonization across jurisdictions, and the fundamental requirement that oracle-supplied data be independently verifiable and reliable (Stokkink & Pouwelse, 2023).

In conclusion, the technical framework that combines digital carbon footprint modeling for metaverse transactions, blockchain-based green oracles, and smart contract-driven automated offsetting is strongly supported by current research as a promising solution for transparent and unmanipulable environmental accountability. The conceptual framework describe is supported by recent research as a technically viable approach to transparent digital carbon footprint management using blockchain-based green oracles and smart contracts; however, full-scale implementation is still an area of active development.

3. METHODOLOGY

The nexus of metaverse operations, blockchain technology, and smart contracts is increasingly reshaping the governance of digital carbon footprints. Virtual ecosystems produce significant carbon emissions through hardware utilization, intensive network traffic, and server-side rendering, necessitating a transition from static reporting mechanisms to dynamic environmental oversight. Blockchain technology offers a tamper-resistant infrastructure for monitoring and validating emissions, particularly when integrated with green oracles capable of facilitating real-time data acquisition. Within this framework, smart contracts can operationalize environmental accountability by automating the allocation and retirement of tokenized carbon credits based on real-time emission metrics. Such mechanisms offer an alternative to fragmented and opaque accounting practices by enabling a more transparent and verifiable record of environmental performance. Accordingly, a comparison between conventional carbon-tracking approaches and blockchain-based systems in virtual environments suggests a broader shift toward decentralized, automated, and transparent models of regulatory compliance.

3.1. Comparative Analysis Focus and Key Weaknesses of Traditional Carbon Tracking

Virtual ecosystems, specifically the metaverse, exhibit a structural dichotomy regarding ecological governance that mirrors the tensions inherent in physical supply chains. While traditional carbon-tracking methodologies are characterized by centralized architectures, manual data entry, and procedural latency, blockchain technology offers a paradigmatic shift toward decentralized, tamper-proof, and autonomous carbon tracking. By replacing fragmented and non-transparent reporting systems with a real-time, verifiable ledger, blockchain facilitates a more rigorous alignment between digital economic activities and global sustainability imperatives (Rani et al., 2024).

Across diverse industrial sectors, conventional monitoring, reporting, and verification (MRV) systems rely on manual or semi-manual data entry into centralized databases, supported by periodic third-party audits. This traditional architecture exhibits several systemic vulnerabilities that weaken the effectiveness of ecological governance. The centralization of data frequently produces inconsistent reporting formats and fragmented data silos, leading to significant information asymmetry between emitters, regulators, and verifiers (Almher et al., 2025: 587). Moreover, audit-based ex-post verification processes create temporal delays -reaching approximately 7.5 days in simulated supply chains- while also generating substantial administrative and audit costs (Almher et al., 2025: 592). In addition, manual input procedures and centralized storage structures are inherently prone to human error and intentional manipulation, thereby undermining trust in ESG and carbon disclosure mechanisms (Almher et al., 2025: 587). Finally, traditional MRV frameworks in built environments and carbon markets lack the capacity to provide continuous, high-frequency data streams, which are essential for dynamic optimization and for meeting the complex monitoring requirements of emerging virtual ecosystems (Ojadi et al., 2025: 95-98).

3.2. Advantages of Blockchain-Based Tracking in Virtual Environments

Blockchain-based tracking systems in virtual environments represent a structural shift in environmental governance by replacing periodic, manual reporting with decentralized and immutable ledgers supported by IoT devices and autonomous software agents. This architecture enables source-level data capture, significantly improving the reliability of environmental monitoring processes. In particular, the on-chain recording of emissions and activity data ensures that entries cannot be retroactively altered, thereby reducing fraud risks and preventing "double-counting" in carbon accounting and credit systems (Almher et al.: 594, 2025). As a result, blockchain introduces a higher standard of data integrity compared to traditional centralized reporting frameworks. Beyond data integrity, blockchain integration enhances traceability and audit efficiency across complex supply chains. Through the use of smart contracts and distributed nodes, emissions data can be tracked in near real time, enabling more responsive and transparent oversight mechanisms. Empirical simulations demonstrate that such systems can improve traceability scores by 36% and audit effectiveness by 91% when compared to conventional methodologies (Almher et al., 2025: 587). Additionally, blockchain architectures streamline verification processes by removing intermediaries, leading to cost reductions of up to 70% in certain industrial scenarios. This also reduces administrative burdens and registry-related overheads in carbon trading systems (Almher et al., 2025: 587).

The convergence of blockchain with IoT technologies and digital twins further enables high-frequency, granular data visibility, allowing continuous environmental data streams to be securely recorded on-chain. This level of granularity supports more accurate carbon accounting and facilitates dynamic optimization of energy use and operational efficiency. At the same time, the existence of a single, verifiable ledger accessible to regulators, firms, and users strengthens stakeholder trust and enhances the credibility of ESG reporting frameworks (Kim & Huh, 2020). In the context of the metaverse, these capabilities extend naturally to virtual assets, avatars, and transactions, where smart contracts can embed and enforce carbon-related rules and offset mechanisms for digital activities.

3.3. Tradeoffs and Limitations

Despite the demonstrable advantages of decentralized architectures, blockchain technology is not universally superior and presents significant systemic challenges. A primary concern involves energy consumption and scalability; certain consensus mechanisms. Specifically PoW, are inherently energy-intensive and may paradoxically undermine the net climate benefits sought through digital transformation. Furthermore, the inherent trade-offs between decentralization and throughput often lead to scalability and latency bottlenecks in high-frequency transaction scenarios (Rodrigo et al., 2020). Beyond technical limitations, the implementation and maintenance of blockchain infrastructures require substantial capital expenditures and technical expertise, particularly when integrating decentralized ledgers with physical sensors or legacy enterprise systems (Alotaibi et al., 2024). Finally, the absence of unified global reporting standards and the prevalence of inconsistent regulatory frameworks across jurisdictions further complicate the large-scale adoption of blockchain technology within carbon markets and global supply chains (Kirui et al., 2024: 137).

In summary, empirical research indicates that blockchain-integrated architectures significantly outperform conventional carbon-tracking systems in terms of transparency, traceability, and cost efficiency. However, to ensure environmental sustainability and operational scalability within virtual ecosystems, these systems necessitate rigorous design parameters, including the adoption of energy-efficient consensus mechanisms, the establishment of unified reporting standards, and the implementation of robust governance frameworks. The ecological legitimacy of the metaverse ecosystem should be evaluated not through a reductive approach focusing solely on high energy consumption, but through the technology's potential to substitute physical activities.

This study presents an original net emission balance model (E_{net}) that analyzes the environmental cost savings of digitalization on the same plane.

$$E_{net} = E_{saved} - (E_{device} + E_{network} + E_{server})$$

The equation provides a structured framework for evaluating the net carbon impact of metaverse technologies. Here, Esaved represents emissions avoided by substituting physical activities (such as travel or manufacturing) with virtual alternatives, whereas (Edevice, Enetwork and Eserver capture the operational emissions from end-user devices, data transmission, and server infrastructure, respectively. Recent research highlights both the significant potential for emissions reductions especially in sectors such as transportation, construction, and enterprise collaboration and the substantial risks of increased energy demand if digital infrastructure is not decarbonized or efficiently managed (Liu et al., 2023: 2). The balance between these terms is context-dependent: industrial and enterprise applications often show net savings, whereas consumer metaverse use (e.g., gaming or leisure) may increase overall emissions owing to high device and server energy consumption (Nleya & Velempini, 2024: 23). This review synthesizes current evidence on each term in the equation and discusses when metaverse adoption is likely to yield positive or negative climate outcomes.

Table 1: The meaning of each term

Term	Meaning in formula	Evidence & typical drivers
E_{saved}	Physical activities avoided (flights, hotels, commuting, events, prototyping, factory trials)	Industrial and enterprise metaverse use (digital twins, remote meetings, virtual events) can cut travel and physical operations; examples include energy savings in factories and buildings, and reduced travel emissions (De Giovanni, 2023)
E_{device}	End-user hardware energy (VR headsets, PCs, mobiles)	VR headsets ≈10–20 W per user; high-end gamers/VR users can reach ~0.91 tCO_2/year in intensive scenarios (Al-Kfairy, 2025)

Term	Meaning in formula	Evidence & typical drivers
$E_{network}$	Telecom and data transmission	5G/edge networks and cloud gaming/ VR streaming are highly energy intensive; cloud/VR traffic is a major share of Information and Communication Technologies (ICT) energy and CO_2 (Viola et al., 2025)
E_{server}	Data center + rendering + blockchain	Data centers and cloud rendering dominate backend energy; metaverse blockchain/economy layer may grow >8× 2022–2030 and become a major share of energy use (De Giovanni, 2023; Viola et al., 2025)

Question: Based on the formula, how different might the carbon emissions be if a three-day in-person meeting, which is planned to include air travel, were held in the metaverse area?

Emissions: inperson vs. metaversestyle meeting

For an inperson, 3night meeting, travel, accommodation, and city transport dominate emissions:

- Conference studies find that travel accounts for approximately 55%-95% of the total carbon footprint, while accommodation accounts for another 10%-13%, and local spending and catering account for the remainder (Chuter et al., 2025; Jäckle, 2019: 630-635).
- Example: A large inperson scientific conference emitted 1.3-1.8 ton (t) CO_2e per attendee, almost all from flights (Van Ewijk & Hoekman, 2020); another found 1.4 t CO_2e per attendee, with hotel and venue <5% (Chuter et al., 2025).

In contrast, virtual/online conferences (similar to a “metaverse” meeting) have a far smaller footprint:

- A natural language comments LCA shows that virtual conferencing reduces carbon footprint by ~94% and energy use by 90% relative to in-person events (including food, accommodation, ICT, and transport) (Tao et al., 2021).
- An Indian 3day national virtual conference emitted 6.4 t CO_2e, compared with a modelled 356 t CO_2e (≈55× higher inperson) (Periyasamy et al., 2022).
- Scenario analysis for 3D/6G videoconferencing finds that virtual meetings cause only 0.2%-0.9% of the emissions of a meandistance physical business trip (Seidel et al., 2021).

- A VR/metaverse meeting case study for EU research projects estimates 7-19× lower emissions for VR vs. physical meetings after including VR hardware and information and communication technology lifecycle impacts (Van Thienen et al., 2024).

What the metaverse adds

Metaverse/VR meetings add:

- Device manufacturing and ewaste, as well as data center and network energy use (Esposito et al,., 2025: 7-15).
- However, current evidence suggests that when replacing flights and hotels, these digital emissions remain small compared with avoided travel, especially for international or multi-day meetings (Seidel et al., 2021; Tao et al., 2021). Renewable-powered infrastructure further improves this balance (Esposito et al., 2025: 7-15)

Replacing a 3night, travelintensive meeting with a metaverse/VR meeting of similar duration and participation would, based on current studies, likely cut perperson emissions by roughly 90-99%, as it removes flights, hotel stays, and most local transport while adding only modest ICTrelated emissions. The reviewed literature supports the utility of your equation as a conceptual tool: the net climate benefit from metaverse adoption hinges on maximizing while minimizing device/network/server emissions through efficiency improvements and clean energy sourcing (Dinçer et al., 2022: 36; Liu et al., 2023: 5). Industrial applications, where large-scale travel or resource-intensive processes are replaced, show strong evidence for a positive net impact (Nleya & Velempini, 2024: 25). However, consumer-facing uses risk negative outcomes unless paired with decarbonized infrastructure and responsible device management. Rebound effects remain a concern. Increased accessibility may drive new forms of consumption that erode initial gains unless carefully regulated or incentivized toward true substitution rather than supplementation (Pellegrino et al., 2023: 13).

In summary, this methodology provides a robust framework for quantifying the ecological impact of the metaverse using blockchain-based carbon management. By implementing the Enet formula within a transparent digital ledger system and validating it with real-world data center experiments, this approach enables detailed monitoring and policy-compliant reporting of environmental performance in digital ecosystems.

4. POLICY IMPLICATIONS AND SOLUTIONS

Policymakers are deepening their work on advanced legal and financial instruments to encourage the adoption of sustainable protocols in metaverse and blockchain ecosystems (Sadawi et al., 2021). This includes exploring strategic interventions, such as deterrent tax regulations for high-carbon-intensity blockchain operations and the imposition of progressive administrative fines and access restrictions on platforms exceeding emission thresholds. The integration of blockchain technology into existing emissions trading systems (ETS) is critical for standardizing carbon accounting practices across different jurisdictions and ensuring alignment with global climate goals, such as the SDGs (Lanteri et al., 2025). Regulatory frameworks developed through this process include the recognition of tokenized carbon credits as digital assets subject to property law and affirmative action mechanisms, such as tax incentives for platforms that automatically offset carbon through smart contracts (Kurt and Alsu, 2024: 217).

The integration of blockchain-based oracle systems into energy network Enet formulations offers a transformative approach to carbon footprint management, enabling real-time, tamper-proof, and transparent emissions data. This technological advancement supports the development of robust policy frameworks that can drive carbon neutrality, enhance market integrity, and incentivize sustainable practices. The following review synthesizes current research to assess the viability of four key policy recommendations. These are emission licensing and transparency, legal status of carbon credits, incentive and sanction regimes and last interoperability of carbon credits. Evidence from recent studies highlights the role of fintech and blockchain in promoting green finance, improving environmental reporting accuracy, and supporting regulatory innovation (Tuğaç: 2023: 84; Addy et al., 2024: 762-763). These findings provide a strong foundation for policy solutions that leverage digital verification to achieve climate goals.

4.1. Emission Licensing, RealTime Transparency

Ensuring environmental sustainability within the metaverse ecosystem necessitates the establishment of a concrete and auditable foundation for the physical world impacts of digital activities. In this context, evidence indicates that mandatory and detailed greenhouse gas emission disclosures, alongside benchmarking initiatives, play a critical role in reducing emissions and enhancing corporate accountability. Blockchain-based measurement, reporting, and verification (MRV) systems have the potential to significantly reduce administrative costs, particularly within structures such as emission trading systems (ETS). By leveraging the immutable nature of the technology, these systems enhance traceability and minimize the risks of fraud in carbon accounting (Özdemir, 2024: 309; Traub et al., 2025).

The utilization of verified data through green oracles, which lie at the heart of this architecture, enables platform operators to substantiate their environmental impacts instantaneously. Requiring operators to document their real-time neutrality through this method is in alignment with the duty of care principle in information technology law and supports global calls for more rigorous, standardized, and transparent reporting frameworks (Liu et al., 2022: 46). The proposed regulatory framework strikes a fair balance between digital property rights and collective environmental rights, thereby securing the ecological legitimacy of the metaverse.

4.2. Legal Status of Tokenized Carbon Credits

The burgeoning literature on carbon markets emphasizes that the transition to a digitalized climate economy necessitates a precise legal definition of property rights regarding carbon units, alongside a robust regulatory framework for smart contract operations and liability. Legal scholarship on tokenized and digital assets increasingly advocates for treating tokens as legally enforceable rights or digital property, provided that the nexus between the underlying asset and the digital representation is clearly codified in statute (Lavayssière, 2025: 2). In the absence of such statutory clarity, the 'code is law' paradigm risks conflicting with established public law oversight and constitutional protections.

Current reviews identify interoperability and market fragmentation as the primary obstacles to large-scale adoption. To mitigate these barriers, scholars have recommended the harmonization of standards and the cross-jurisdictional legal enforcement of carbon-credit property rights. This includes formalizing registry links across diverse digital ecosystems to prevent double-counting and information asymmetry. In this context, legally guaranteeing the portability of oracle-verified carbon credits between metaverse platforms aligns with the global call for standardized, tokenized credits hosted on linked registries. Such portability is essential to resolve the ownership paradox where the potential termination of an energy-intensive platform might otherwise result in the unlawful deprivation of a user's digital property (Çetin, 2025: 625-626; Lavayssière, 2025: 4). By establishing these credits as "digital assets" subject to property law, the proposed framework ensures that environmental compliance does not compromise the security of digital tenure

4.3. Incentives, Sanctions, and NetZero

The prevailing literature on carbon markets emphasizes a multidimensional approach to ecological governance, primarily grounded in the 'polluter pays' principle. Recent studies have advocated for a combination of carbon pricing and targeted fiscal instruments, such as differentiated energy taxation and specific levies on high-carbon blockchain operations, to catalyze a shift toward energy-efficient consensus mechanisms and verifiable emission reductions (Li et al., 2020). Issues such as the discovery of transactions conducted within the metaverse are likely to become subjects of increasing legal and regulatory inquiry as metaverse environments continue to develop and expand (Bozdoğanoğlu, 2023: 221).

Furthermore, the integration of ESG-linked incentives and mandatory high-quality disclosure frameworks has been proven to significantly enhance corporate climate performance and stakeholder accountability. By transforming 'soft law' ESG commitments into 'hard law' regulatory requirements, legal frameworks can compel metaverse platforms to internalize their ecological externalities. Under this normative framework, the following policy interventions are proposed, which are consistent with international sustainability imperatives (Li et al., 2020; Traub et al., 2025; Savcı and Yıldırım, 2024: 878). Primarily, fiscal incentives should be introduced, such as granting tax breaks or enhanced ESG credits for platforms that demonstrate verified net-zero status through the Enet model. Alongside these incentives, administrative sanctions must be implemented, including escalating financial penalties or temporary access restrictions for platforms that persistently exceed established emission thresholds. Finally, imposing differentiated obligations is necessary to establish higher regulatory compliance standards specifically for platforms utilizing PoW or other energy-intensive architectures.

By leveraging these fiscal and legal tools, regulators can ensure that the metaverse evolves not as an unregulated digital frontier, but as a sustainable ecosystem that aligns with the constitutional duty to protect the environment.

4.4. Interoperability and Portability of Credits

The effectiveness and long-term viability of decentralized carbon markets depend largely on overcoming systemic fragmentation and establishing interoperable governance and technological frameworks. To overcome these obstacles, scholars have advocated for the establishment of harmonized technical standards and the rigorous legal enforcement of property rights associated with carbon credits. This necessitates the creation of secure registry links that transcend individual platform architectures and national jurisdictions, ensuring that carbon units maintain their legal and economic integrity as they traverse different ecosystems (Bahçekapılı, 2025: 374).

In this context, providing a legal guarantee for the portability of oracle-verified carbon credits between metaverse platforms is essential. Such a mandate aligns with emerging calls for standardized, tokenized credits hosted on interoperable or linked registries (Li et al., 2020; Traub et al., 2025). By codifying portability into law, regulators can prevent "digital lock-in" and ensure that environmental obligations specifically those governed by the Enet model are fulfilled through a unified, cross-platform ledger of ecological accountability.

5. DISCUSSION

Empirical research demonstrates that blockchain architectures can significantly enhance transparency and institutional trust within carbon markets by providing immutable ledgers and automated verification protocols (Lanteri et al., 2025). This decentralized framework facilitates the emergence of peer-to-peer (P2P) trading systems, which empower prosumers -individuals who both consume and produce energy- to participate directly in carbon credit markets. By utilizing dynamic pricing mechanisms and tokenized reward systems, these platforms incentivize sustainable behavioral shifts (Karim et al., 2023: 7-15). However, the net environmental utility of these systems is critically contingent upon the underlying consensus protocols. Although decentralized ledgers offer governance benefits, energy-intensive mechanisms, such as PoW, remain fundamentally unsustainable. Consequently, a transition toward proof-of-stake (PoS) or other low-energy alternatives is a technical prerequisite for ecological legitimacy (De Giovanni, 2023).

To align digital innovation with global planetary health goals, proactive policy interventions are essential. This study recommends implementing the following best practices (Sadawi et al., 2021; Damayanti et al., 2024: 49). First, fiscal instruments should be deployed, such as targeted taxes on high-emission mining operations and energy-intensive digital activities. Additionally, regulatory mandates must be established to legally require data centers and metaverse platforms to operate exclusively on renewable energy sources. It is also crucial to develop standardized digital environmental impact assessments (D-EIA) specifically for virtual projects, analogous to existing Leadership in Energy and Environmental Design (LEED) or International Organization for Standardization (ISO) frameworks. Finally, promoting cross-border jurisdictional cooperation to harmonize digital governance is vital to prevent regulatory arbitrage within decentralized carbon markets.

Despite these advancements, several structural limitations persist that must be addressed in future legislative frameworks. The lack of universal standards for emissions accounting across divergent jurisdictions creates significant reporting gaps. Furthermore, the insufficient integration between physical and virtual regulatory regimes often leads to the decoupling of digital activities from their real-world ecological costs. Without robust third-party audits and green oracle verification, the risk of greenwashing[2] remains high. Finally, persistent socioeconomic inequities regarding access to green infrastructure and unresolved scalability bottlenecks continue to challenge the universal adoption of decentralized sustainability models.

CONCLUSIONS

The rapid expansion of the metaverse ecosystem presents a dualistic challenge to global climate governance, oscillating between the potential for significant decarbonization through virtualization and the risk

2- It refers to the efforts of a company, institution, or system to project an eco-friendly, sustainable and green public image, even though it actually harms the environment or does not do enough to protect it.

of escalated energy demands from decentralized infrastructure. This study has demonstrated that the ecological legitimacy of the metaverse cannot be achieved through technical optimization alone; it requires a robust, blockchain-based regulatory framework that bridges the gap between digital innovation and constitutional environmental mandates.

The proposed net emission balance model (E_{net}) provides a normative foundation for evaluating this legitimacy by accounting for both the physical emissions saved through substitution (E_{saved}) and the operational costs of digital architectures ($E_{device} + E_{network} + E_{server}$). An empirical synthesis indicates that while industrial applications often yield a positive net impact, consumer-facing virtual environments require stringent oversight to mitigate rebound effect and systemic inefficiencies. Central to this governance model is the integration of green oracles and smart contracts, which transform the environmental duty of care from an abstract legal principle into an enforceable, real-time administrative reality. By utilizing immutable ledgers, platform operators can substantiate their ecological neutrality, thereby aligning with the SDGs and the CSRD framework.

However, the transition to a sustainable digital frontier necessitates specific policy interventions. This study concludes that policymakers must prioritize the following:

- Explicit legal recognition of tokenized carbon credits as digital property to ensure jurisdictional certainty and prevent the ownership paradox.
- Implementation of fiscal incentives for net-zero platforms and administrative sanctions for energy-intensive PoW protocols.
- Establishing interoperability standards to facilitate the seamless portability of verified carbon assets across fragmented jurisdictions.

In summary, as the metaverse evolves into a pervasive socioeconomic reality, its sustainability remains contingent upon a techno-legal synthesis. By codifying ecological responsibility into the code of virtual interactions, the proposed framework ensures that digital progress remains consistent with the collective right to a healthy environment and the long-term health of the planet.

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METAVERSE'DE AKILLI SÖZLEŞME TABANLI KARBON DENGELEME VE DIJITAL VARLIK TANIMA YÖNTEMLERİYLE HESAP VERİLEBİLİRLİK AÇIĞINI KAPATMAK

Emin GİTMEZ

GENİŞLETİLMİŞ ÖZET

Bu çalışma, sanal gerçeklik, arttırımış gerçeklik ve blokzincir teknolojilerinin kesişiminde hızla büyüyen metaverse ekosisteminin ekolojik meşruiyetini kamu hukuku ve bilişim teknolojileri hukuku perspektifinden ele almaktadır. Sanal evrenlerin fiziksel faaliyetleri ikame ederek kaynak tüketimini azaltma potansiyeli bulunsa da merkeziyetsiz sistemlerin ve veri işleme süreçlerinin yüksek enerji talepleri göz ardı edilemeyecek sistemik çevresel riskler barındırmaktadır. Çalışma, özellikle İş Kanıtı (PoW) gibi enerji yoğun konsensüs mekanizmalarına dayanan yapıların küresel iklim krizini derinleştirme riskini vurgularken, Hisse Kanıtı (PoS) gibi daha çevreci protokollere geçişin önemine dikkat çekmektedir. Çalışmanın merkezinde, merkeziyetsiz dijital alanlarda geleneksel "kirleten öder" ilkesinin ve devletin çevreyi koruma ödevinin önünde duran sorumluluk boşluğu yer almaktadır. Sanal dünyada kirletici kimliğinin platform operatörleri, akıllı sözleşme geliştiricileri ve kullanıcılar arasında parçalanmış olması, hukuki muhataplık krizine yol açmaktadır. Bu boşluğu doldurmak amacıyla araştırma, özgün bir Net Emisyon Dengesi Modeli (E_{net}) geliştirmektedir. Geliştirilen formül, dijitalleşmenin seyahat, prototipleme veya fiziksel organizasyonların iptali gibi yollarla sağladığı karbon tasarrufunu (E_{saved}); son kullanıcı cihazları, ağ altyapısı ve sunucu operasyonlarının harcadığı enerjiyle ($E_{device} + E_{network} + E_{server}$) aynı düzlemde ölçerek metaversün gerçek iklim etkisini ortaya koymaktadır. Literatür analizi ve senaryo simülasyonları, endüstriyel ve kurumsal kullanımlarda net tasarruf oranlarının %90 ila %99 seviyelerine ulaşabildiğini, ancak tüketici odaklı eğlence kullanımlarında altyapı temiz enerjiyle beslenmediği takdirde emisyonların artabileceğini göstermektedir.

Teknolojik çözüm katmanında ise çalışma, yeşil oracle mimarisi ile akıllı sözleşmelerin entegrasyonunu önermektedir. Nesnelerin interneti (IoT) sensörlerinden ve akıllı sayaçlardan gelen gerçek zamanlı emisyon verilerinin blokzincire aktarılmasıyla, geriye dönük manipülasyonu imkansız kılan bir ölümsüz kanıt sistemi inşa edilmektedir. Bu verilerle çalışan akıllı

sözleşmeler aracılığıyla, metaversede üretilen dijital karbon ayak izi anlık olarak hesaplanmakta ve tokenize edilmiş karbon kredileriyle gerçek zamanlı olarak otomatik mahsup edilmektedir.

Çalışmanın en özgün hukuki ve politik katkılarından biri, tokenize karbon kredilerinin mülkiyet hukuku kapsamında birer dijital varlık olarak tanınması yönündeki teklifidir. Bu yaklaşım, çevre mevzuatına uyumu güvence altına alırken dijital mülkiyet haklarını korumakta ve bir platformun kapanması durumunda kullanıcının hak mahrumiyetine uğramasını engelleyen mülkiyet paradoksunu çözmektedir. Bununla birlikte akıllı sözleşmelerin sadece teknik otomasyon sağlayan kod blokları olarak kalmaması, bu dijital yükümlülüklerin mevcut kamu hukuku denetimiyle ve özellikle özel hukuk ilkeleriyle uyumlu hale getirilerek yasal olarak uygulanabilir kılınması yönünde özgün bir yapı kurulmuştur.

Politika yapıcılar için geliştirilen somut çözüm önerileri kapsamında çalışma, yumuşak hukuk (soft law) niteliğindeki kurumsal sosyal sorumluluk taahhütlerinin, bağlayıcı sert hukuk (hard law) kurallarına dönüştürülmesini savunmaktadır. Bu doğrultuda; platformlara yönelik zorunlu emisyon lisanslaması getirilmesi, enerji yoğun PoW protokollerine caydırıcı vergiler uygulanması, yeşil akıllı sözleşme kullanan platformlara mali teşvikler sağlanması ve platformlar arası dijital kilitlenmeyi önleyecek yasal olarak güvenceye alınmış çapraz platformların birlikte çalışabilirliği şart koşulmaktadır. Ayrıca sanal projeler için geleneksel ÇED raporlarının muadili olacak "Dijital Çevresel Etki Değerlendirmesi-(D-ÇED)" standartlarının geliştirilmesi ve sınır ötesi mevzuat farklılıklarını engellemek amacıyla uluslararası yargısal iş birliğinin artırılması gerekliliği ortaya konmaktadır.

Sonuç olarak çalışma; metaversün ekolojik meşruiyetinin yalnızca teknik optimizasyonla değil, anayasal çevre haklarını sanal evrenin kod yapısına entegre eden tekno-hukuki bir sentezle mümkün olacağını kanıtlamaktadır. Önerilen model, bilişim teknolojileri hukukunun kapsamını veri gizliliği sınırlarından çıkararak kolektif ekolojik sorumluluk katmanına taşımaktadır. Bununla birlikte, dijital büyümenin dünyanın uzun vadeli gelişimiyle uyumlu olmasını sağlayacak normatif bir temel sunmaktadır. Ek olarak çalışma; veri ve siber güvenlik odaklı bilişim hukuku ile anayasal çevre hukukunu, akıllı sözleşmeler ve çalışmada belirtilen model üzerinden tekno-hukuki bir sentezle birleştirerek bütüncül bir dijital karbon yönetişim mekanizması inşa etmektedir.