

RESEARCH ARTICLE

Metaverse and NFT-Based Digital Ecosystems: Sustainability, Governance, and Energy Trade-Offs

Vincenzo de Masi^{1,*}  and Ernestina Xinyi Zhu² 

¹*School of Journalism and Communication, Guangdong University of Foreign Studies, China*

²*Alliance Manchester Business School, University of Manchester, UK*

Abstract: Metaverse platforms and non-fungible token (NFT) markets are often framed as immaterial, frictionless layers of the digital economy. However, their expansion depends on energy-intensive infrastructures, complex governance arrangements, and regulatory choices that can amplify or mitigate environmental externalities. This article examines sustainability, governance, and energy trade-offs in metaverse and NFT-based ecosystems. The research treats China as a policy and regulatory laboratory. This is to explore the ideas of how “digital collectibles” and platform-based experiments have evolved under tighter constraints on cryptocurrency circulation. Building on a socio-technical perspective, the paper connects three levels of analysis. It maps the material footprint of immersive experiences and tokenized assets, focusing on consensus mechanisms, cloud and data center dependencies, and the risk of rebound effects. The exploration of governance addresses technical standards and platform accountability. In the meantime, it discusses the tensions between openness, interoperability, and enforceable rules. A comparison of regulatory pathways addresses their implications for sustainability metrics, user rights, and market design. The contribution of this research lies in the framework for evaluating whether metaverse and NFT ecosystems can credibly align with sustainability goals without relying on rhetorical “green” narratives. This research also proposes governance levers that make environmental accounting and accountability operational rather than aspirational.

Keywords: NFT, digital ecosystems, platform governance, energy consumption, Chinese regulations

1. Introduction

Metaverse and NFTs are frequently described through narratives of dematerialization, where value creation shifts from physical goods to symbolic assets, experiential services, and digitally mediated sociality. This framing has practical consequences. It encourages policymakers, firms, and researchers to prioritize issues of market growth, user engagement, and innovation velocity, while treating environmental costs as secondary or solvable through incremental efficiency. A more defensible starting point is to treat metaverse and NFT-based ecosystems as material digital systems that reallocate, rather than eliminate, resource use. Their sustainability profile depends on how compute is provisioned, how tokenization is implemented, and how governance determines accountability and enforceability across platforms and jurisdictions [1–3].

Stated explicitly, the research problem addressed in this article is that sustainability claims about metaverse and NFT-based ecosystems are routinely asserted through dematerialization rhetoric without being systematically tested against infrastructure dependencies, market design incentives, and governance

enforceability. The objectives of the study follow directly from this problem: (1) to map the infrastructure reality of immersive and tokenized systems, including compute, device, and network dependencies; (2) to analyze how market design and incentive structures shape throughput, speculation, and rebound effects; and (3) to evaluate the governance architectures that determine whether sustainability claims are measurable, auditable, and enforceable. The research gap this paper addresses is that existing scholarship tends to treat blockchain energy use, metaverse platform governance, and jurisdiction-specific regulatory design (including China’s constrained tokenization model) as separate literatures; this article’s contribution is to integrate these three strands into a single governance-informed evaluation framework.

Two cautions guide this analysis. Describing an ecosystem as “digital” does not automatically make it “lightweight.” Immersive environments, persistent worlds, and tokenized markets are coupled to data centers, networks, end-user devices, and the software stacks that orchestrate them. Their environmental footprint therefore emerges from an interaction between infrastructure demand and user scale, including device replacement cycles and content production intensities [1, 3]. Rebound effects can also offset sustainability outcomes. Efficiency gains may reduce per-transaction or per-user impacts while accelerating adoption, total usage, and

*Corresponding author: Vincenzo de Masi, School of Journalism and Communication, Guangdong University of Foreign Studies, China. Email: 202530001@gdufs.edu.cn

speculative activity, which can raise absolute energy demand and emissions even when unit costs fall [1, 3].

Within NFT ecosystems, the most visible sustainability controversy has been the energy cost of blockchain validation, especially in proof-of-work systems. Over the last few years, the debate has matured from anecdotal “carbon blame” to more systematic attempts to quantify lifecycle implications and to distinguish between consensus mechanisms, marketplace design, and offset practices [4, 5]. However, treating NFTs purely as a blockchain problem is analytically incomplete. NFTs operate inside wider socio-technical arrangements that include marketplaces, custodial layers, identity systems, moderation policies, and cross-platform interoperability. In practice, the sustainability question becomes inseparable from governance. Decisions about what is permitted, what is measured, and what is auditable determine whether environmental claims can be verified or remain performative [2, 6, 7].

Governance is similarly central to metaverse systems. Interoperability and user safety, data protection and identity, and the rules that constrain harmful conduct must be negotiated across heterogeneous technical standards and institutional settings. A growing body of work argues that metaverse governance should be approached through technical standards and phased governance frameworks, in which the state, industry, and multi-stakeholder actors co-produce enforceable baselines rather than relying on purely voluntary self-regulation [6]. In parallel, public institutions have highlighted the regulatory tensions created by immersive systems, including the challenges of device interconnection, cross-border data flows, identity management, and platform accountability [8].

China is a particularly revealing case for studying these intersections because it combines strong platform industrial capacity with comparatively restrictive approaches to cryptocurrency circulation. As a result, NFT-like markets have often been reframed as “digital collectibles” embedded in permissioned or semi-permissioned infrastructures, coupled to payment constraints, resale restrictions, and platform-level compliance mechanisms. This configuration makes China a regulatory laboratory where tokenized markets and immersive platformization evolve under policy objectives that prioritize controllability, risk containment, and alignment with national digital strategies. Analyses of China’s blockchain trajectory emphasize how state-led infrastructure and governance ambitions can reshape blockchain adoption, standards, and international influence [9, 10]. More recent discussions of digital governance similarly underline how China is exploring governance approaches across artificial intelligence (AI) and digital assets, highlighting the institutional experimentation that accompanies new technological capabilities [11].

This article uses China’s environment not to claim that one model is universally preferable but to clarify what sustainability, governance, and energy trade-offs look like when tokenization is embedded in more tightly governed platforms. The central argument is that metaverse and NFT ecosystems should be evaluated through a combined framework with three layers. Infrastructure reality encompasses compute intensity, device and network dependencies, and the boundary conditions of measurement. Market design and incentives shape the conditions under which speculation, scarcity engineering, and reward systems can increase throughput and consumption even under more efficient technical protocols [1, 3]. Governance architecture determines whether sustainability targets can be enforced through reporting standards, auditability, and meaningful accountability mechanisms [6, 7]. When these layers are analyzed together, the research

question shifts from “Are NFTs or metaverse systems sustainable?” to “Under what governance constraints and technical configurations can sustainability claims be made credible, measurable, and enforceable, and what are the unavoidable trade-offs?”

The remainder of the paper proceeds as follows. Section 2 clarifies the conceptual background, connecting Web3 imaginaries to the material and institutional conditions that enable tokenized and immersive systems. Section 3 explains the method and sources used, including comparative policy and governance analysis, and a synthesis of technical and sustainability literature. Section 4 positions China as a regulatory laboratory, highlighting how constraints and policy priorities shape platform practices. Sections 5 and 6 develop the sustainability and governance analysis, with particular attention to energy accounting, rebound effects, and standards-driven governance. The conclusion consolidates a set of evaluation criteria and governance levers that are applicable beyond China, while remaining sensitive to jurisdictional differences.

This analysis is explicitly positioned within financial technology (FinTech) and sustainable digital finance scholarship. NFTs and digital collectibles are forms of tokenized ownership that function as financial instruments: They enable price formation, secondary-market trading, and value transfer through marketplace infrastructures that resemble other FinTech innovations in payments and asset digitization. Marketplace design choices, such as resale restrictions, payment-rail constraints, and royalty mechanisms, are financial-market design decisions with direct implications for transaction throughput and, consequently, energy demand. Viewed this way, the governance of tokenized ownership is inseparable from the governance of sustainable digital finance, and the China case illustrates how financial-market constraints on token circulation can simultaneously serve risk-containment and environmental objectives.

2. Literature Review

The contemporary vocabulary surrounding the metaverse and NFTs is strongly shaped by Web3 imaginaries. In policy discourse and industry communication, Web3 is frequently framed through decentralization, user sovereignty, and programmable ownership, often implying that new ecosystems of value can emerge with limited dependence on dominant intermediaries. These narratives matter because they influence how metaverse projects are justified, how tokenized markets are designed, and how sustainability claims are communicated. Yet Web3 imaginaries can also generate analytical blind spots. They may foreground symbolic notions of “virtuality” and “dematerialization” while downplaying the energy dependencies, infrastructural constraints, and institutional arrangements that make immersive and tokenized systems operable at scale [1, 3].

A socio-technical ecosystem approach provides a more defensible entry point. Rather than treating the metaverse as a single technology or a coherent “next internet,” this paper treats metaverse systems as layered ecosystems where immersive interaction, platform governance, and tokenized market infrastructures converge. NFTs, in this ecosystem view, are not merely digital collectibles but a market mechanism that enables ownership claims, monetization, and price formation inside platform-controlled environments. Sustainability becomes inseparable from this architecture because environmental impacts are produced through how compute is provisioned, how tokenization is implemented,

and how governance determines accountability and enforceability across platforms and jurisdictions [1–3].

China is especially useful for refining this conceptualization. The Chinese digital environment demonstrates how tokenized markets and immersive platformization can develop under tighter constraints on cryptocurrency circulation and under a governance logic oriented to controllability and risk containment. This setting allows a clearer separation between the technical possibility of tokenization and the institutional design of markets, including rules about resale, platform responsibility, and the boundary between “digital collectibles” and speculative crypto-assets [9–11].

2.1. Ecosystems, not objects

An ecosystem perspective avoids two reductions that often distort sustainability debates. The first reduction treats NFTs as a narrow blockchain artifact and evaluates environmental impact mainly through consensus mechanisms. The second reduction treats the metaverse as a spatial metaphor, a “virtual world” conceptually detached from digital industrial organization. Both reductions are incomplete. NFT activity is mediated through marketplaces, custodial services, user interfaces, payment infrastructures, compliance filters, and platform policies. Likewise, metaverse experiences are mediated through platform architectures, content moderation, identity systems, and infrastructure provisioning rather than existing as free-floating “spaces.” The sustainability question therefore cannot be answered by asking whether NFTs or the metaverse are “good” or “bad” for the environment. It must be reframed as an ecosystem problem that depends on growth dynamics, incentive structures, and governance constraints [1–3].

This ecosystem framing is consistent with research emphasizing that metaverse systems can be simultaneously pollution reducing and pollution generating. Substitution effects can occur when remote collaboration reduces travel, when simulation optimizes physical processes, or when digital twins reduce waste. Yet increased engagement, higher-resolution media, and always-on connectivity can offset or exceed those savings by expanding infrastructure demand. The relevant unit of analysis becomes the aggregate ecosystem and its expansion trajectory rather than isolated activities [1, 2]. This is particularly salient in China, where large-scale platform adoption can turn marginal design choices into system-level energy consequences.

2.2. Dematerialization narratives and rebound dynamics

Dematerialization is one of the most persistent rhetorical supports for sustainability claims in metaverse discourse. The underlying idea is that shifting consumption from physical goods to virtual goods or experiences reduces material throughput. The claim is not entirely unfounded; some digital activities can displace material flows and reduce emissions in specific contexts. However, the dematerialization thesis becomes fragile when it assumes that digital substitution is environmentally neutral by default. Related work on digitalization-to-emissions trade-offs emphasizes that efficiency gains can coexist with increased absolute emissions when adoption accelerates and usage intensifies, producing rebound effects [1].

Rebound dynamics are structurally likely in metaverse ecosystems because the economic logic of platform economies rewards scale. The rebound question is particularly relevant in China, where extremely large user bases and rapid platform

diffusion can amplify these dynamics. A conceptual framework that ignores rebound risks conflates “efficiency” with “sustainability” and understates ecosystem-level impacts [1, 2].

2.3. NFTs as programmable ownership and market design

NFTs are best understood as programmable ownership claims attached to digital assets within market infrastructures. Their practical meaning is defined by how marketplaces structure scarcity, resale, royalties, and discoverability; how assets are hosted and linked; and how identity, fraud detection, and compliance measures are enforced. The sustainability controversy around NFTs has often been narrated as a dispute about blockchain electricity use, especially in proof-of-work systems.

A crucial point, often missed in generic debates, is that NFT sustainability is also a function of market design. Marketplaces can encourage high-frequency trading and speculative churn, or they can constrain resale and throttle throughput. They can prioritize custodial designs that reduce complexity but increase platform control, or they can enable non-custodial designs with broader externalities. China is instructive here because the “digital collectibles” model has frequently been coupled with constraints on resale and payments, suggesting that tokenization can be embedded into more restrictive market architectures that reduce speculative throughput even while supporting digital ownership claims [9–11]. This is not presented as inherently superior, but it clarifies that “NFTs” are not a single environmental object; they are an institutional form whose footprint varies with governance.

2.4. Typology of metaverse architectures and sustainability implications

A further conceptual clarification concerns the heterogeneity of metaverse architectures. The term “metaverse” groups together systems that differ substantially in technical structure and governance. A basic typology is helpful for sustainability analysis.

In platform-centric metaverse systems, a dominant operator controls identity, assets, rules, and interoperability. These systems are typically easier to regulate and can implement efficiency measures or disclosure requirements through centralized governance, but they can also obscure externalities if transparency is weak. Federated or interoperable systems instead rely on multiple platforms seeking interoperability through shared standards. These systems create governance coordination challenges because sustainability metrics and auditing must be aligned across actors. Ledger-anchored systems embed tokenization and verification more deeply into the architecture. Here, sustainability questions are strongly affected by verification design, consensus mechanisms, and the environmental profile of the underlying infrastructure.

China’s digital environment contains strong examples of platform-centric architectures and also illustrates a tendency toward permissioned or semi-permissioned infrastructures for tokenized assets. This configuration is relevant because it provides a setting in which sustainability levers, such as reporting obligations or infrastructure standards, may be implemented through a smaller number of large actors and state-linked governance channels [9–11]. It also highlights a conceptual tension: Platform-centric governance can make enforcement feasible, but it can also concentrate informational power in ways that complicate independent verification. Table 1 provides a demonstration

Table 1
Metaverse/NFT architecture types and their sustainability implications

Architecture type	Governance feature	Sustainability implication	China illustration
Platform-centric	Single operator controls identity, assets, and rules	Easier to enforce disclosure, but transparency depends entirely on operator goodwill	Dominant Chinese platforms hosting digital collectibles
Federated/interoperable	Multiple platforms coordinate via shared technical standards	Comparable metrics are possible, but cross-actor auditing coordination is costly	Limited; standards capacity is largely state-coordinated rather than multi-platform
Ledger-anchored	Tokenization and verification embedded in protocol architecture	Strongly affected by consensus-mechanism choice and on-chain throughput	Constrained via permissioned/semi-permissioned designs rather than open ledgers

of metaverse/NFT architecture types and their sustainability implications.

2.5. Infrastructure stack, system boundaries, and what counts as “impact”

The sustainability profile of metaverse and NFT ecosystems depends on how system boundaries are drawn. A credible assessment requires explicit boundary choices and transparency about what is included and excluded. At minimum, four infrastructure layers are relevant.

The first layer is the device and interface layer, including headsets, smartphones, personal computers, sensors, and their replacement cycles. The second is the network layer, including mobile and fixed connectivity, edge computing, content delivery, and the energy costs of data transmission. The third is the cloud and data-center layer, where rendering support, AI services, storage, and orchestration are provisioned. The fourth is the verification and market layer, which includes blockchain or quasi-blockchain infrastructures, token issuance, marketplace operations, and related services.

2.6. Governance as a sustainability determinant

Governance affects sustainability through architecture and accountability. It shapes architectural choices by influencing whether ecosystems prioritize openness, interoperability, and frictionless exchange or whether they embed constraints that limit risk and throughput. Accountability depends on governance rules that define what is measured, how risks are audited, and how externalities are assigned. Policy-facing institutional analyses highlight complementary tensions around identity, data protection, and cross-platform interoperability, which indirectly affect sustainability because governance choices shape architecture and infrastructure scaling [8]. United Nations Educational, Scientific and Cultural Organization (UNESCO)’s platform governance principles reinforce the practical relevance of transparency, checks and balances, and multi-stakeholder governance, offering a foundation for accountability frameworks that can be extended to sustainability reporting and verification [10].

China’s laboratory is again informative. State capacity to impose platform rules and to steer industrial policy can translate into enforceable governance constraints, including disclosure expectations and compliance requirements. At the same time, this configuration can produce uneven transparency and limit independent auditing, which matters when environmental claims are used to legitimize new digital markets. Governance is therefore

not merely a background condition; it is a sustainability determinant that shapes whether environmental accounting is operational or symbolic [6–11].

2.7. Analytical implications for the rest of the paper

The conceptual framework developed in this section treats metaverse and NFT systems as socio-technical ecosystems rather than isolated technologies. Evaluating their sustainability claims requires explicit system boundaries and attention to rebound and displacement effects rather than reliance on dematerialization rhetoric. Governance and market design are integral to this assessment because they shape energy demand, transaction throughput, transparency, and auditability.

3. Research Methodology

The paper is built on a structured synthesis of peer-reviewed research, institutional and policy documents, and jurisdiction-specific legal and regulatory analyses. The goal is to keep the analytical focus on mechanisms rather than on a single footprint estimate because the environmental profile of metaverse and NFT-based ecosystems is produced by coupled layers that include verification design, infrastructure provisioning, platform rules, and regulatory supervision [1–3].

To make the review procedure transparent and reproducible, this paper is explicitly classified as a structured, mechanism-focused narrative synthesis rather than a systematic, semi-systematic, or purely interpretive review. This classification was chosen because the research question concerns how mechanisms (verification design, infrastructure provisioning, governance architecture) interact across heterogeneous source types, rather than estimating a single quantitative effect size, which a systematic review protocol is better suited to. Sources were identified through targeted searches of academic databases (Scopus, Web of Science, Google Scholar) and institutional or policy repositories (United Nations Conference on Trade and Development (UNCTAD), UNESCO, European Parliament, Chinese regulatory and industry publications), using combinations of the terms metaverse, NFT, blockchain energy, digital collectibles, platform governance, data-center sustainability, and China digital regulation. Sources were included if they directly addressed at least one of the three analytical layers used in this paper (infrastructure and energy mechanisms, market design and tokenization, or governance and regulatory architecture) and were published predominantly between 2021 and 2026, with earlier foundational sources retained where still authoritative. Sources were excluded

if they addressed metaverse or NFT topics only tangentially, or if institutional materials could not be corroborated by at least one independent source. Within these boundaries, the synthesis proceeds thematically rather than chronologically, organizing sources by analytical layer rather than by publication date, consistent with the conceptual aims of the paper.

The first concern is NFT-related sustainability and variability. This is introduced by different blockchain architectures and governance interventions. Empirical work on NFT emissions and carbon debt provides a starting point for understanding how impacts scale with market activity and how the framing of “digital ownership” can obscure upstream costs [4]. Policy-oriented scholarship further emphasizes that sustainability is not a peripheral externality but a design and governance problem embedded in consensus protocols and institutional choices [12]. To avoid treating “blockchain energy” as a monolithic issue, the analysis incorporates consensus-focused reviews that compare energy implications across protocol families and highlight the security–efficiency–decentralization trade-offs that shape sustainability outcomes [13, 14]. This is complemented by sources that discuss how Web3 sustainability is increasingly linked to disclosure and measurement standards, including proposals for verification practices and reporting discipline rather than voluntary claims [14, 15].

The second concerns are in the infrastructure layer. Because immersive ecosystems depend on cloud and data-center provisioning, the analysis uses authoritative assessments of data centers and data transmission networks as a baseline for understanding why metaverse-scale persistence cannot be evaluated independently from wider infrastructure trajectories [16]. This is paired with more recent evidence on AI servers and accelerated computing, which highlights the combined pressures of electricity, water, and carbon intensity, and shows why “efficiency gains” alone may not stabilize absolute environmental impact when demand grows [17]. To ensure that the infrastructure discussion remains anchored in operational realities, the article also draws on specialist analyses of cooling and high-density compute strategies, as well as water-use constraints associated with data-center expansion, treating these sources as contextual documentation of technical pathways rather than as causal proof [16, 18, 19]. Finally, China-specific empirical research on digital infrastructure and environmental outcomes is used to situate the infrastructure debate within a governance environment where industrial policy and sustainability targets interact, rather than evolving independently [5, 20].

As for the third one, it is about governance and regulation. The reason is that sustainability claims in metaverse and NFT ecosystems ultimately depend on what is disclosed, what can be audited, and what can be enforced. The analysis therefore includes standards-oriented proposals that conceptualize metaverse governance through technical standards, phased policy design, and structured coordination across public and private actors [6]. Institutional policy documents are used to capture regulatory tensions around identity, data governance, and interoperability, which indirectly shape architecture and thus sustainability impacts [8]. UNESCO’s platform governance guidelines inform the accountability dimension of the analysis by providing principles that can be translated into practical disclosure and oversight expectations, including transparency, checks and balances, and multi-stakeholder governance [7]. Comparative work on national metaverse policies and cross-jurisdictional legal frameworks is included to prevent overfitting the argument to one institutional setting and to clarify the spectrum of governance models across state-driven and market-driven regimes [21, 22].

Within this governance corpus, China-related sources are treated as central because the paper explicitly uses China as a regulatory laboratory. Strategy and policy analyses of China’s blockchain trajectory clarify how state-led infrastructure ambitions and governance logics shape adoption pathways and influence the institutional framing of tokenized ecosystems [9, 10]. Research on China’s platform regulation and enforcement variability further supports the argument that governance capacity, compliance incentives, and ex ante regulatory tools can materially affect ecosystem design and accountability practices [23, 24]. Legal briefings and jurisdictional updates on NFTs and “digital collectibles” are used to document how market design constraints, including restrictions on resale and the separation between collectibles and cryptocurrency markets, shape the operational form of tokenized ownership in China and adjacent jurisdictions [17, 25]. These sources are not treated as a substitute for peer-reviewed evidence; they are used to document governance mechanisms that are otherwise under-specified in academic treatments. Where relevant, China-facing compliance materials on data governance and infrastructure regulation provide additional context for why sustainability accounting and platform accountability are increasingly tied to broader regulatory modernization, especially in cross-border data handling and audit intensity [26–28].

The analytical procedure begins by specifying system boundaries explicitly to avoid selective accounting, distinguishing device and interface dependencies, network and transmission costs, cloud and data-center provisioning, and the verification and market layer where tokenization is implemented [1, 6, 9]. Within these boundaries, the synthesis of sustainability evidence connects NFT emissions debates and protocol variability to the infrastructure realities of data-center growth and AI workloads, while remaining attentive to rebound effects and displacement rather than assuming automatic dematerialization benefits [1, 4, 12, 17]. The governance analysis applies a standards-and-accountability lens to examine how disclosure expectations, auditability, and enforcement structures shape what sustainability claims can credibly mean in practice [6–8]. The China case shows how constrained market design and compliance architectures can reshape tokenized ecosystems, while also illustrating the limits of transparency and the need for independent verification in any sustainability narrative [14, 23, 24, 29].

Two scope conditions are important. The paper does not claim direct measurement of platform-specific energy use; instead, it clarifies the mechanisms and governance levers that enable measurement, comparability, and enforceability across ecosystems [6, 7, 14, 15]. In addition, the China laboratory is used to clarify institutional mechanisms, not to propose a universally transferable model. The comparative materials are therefore used to highlight what is context-specific versus what is structurally likely across jurisdictions when tokenized markets and immersive platforms scale under different governance regimes [21, 22, 24].

4. China as a Regulatory Laboratory for Tokenized Digital Goods and Immersive Platforms

China provides a distinctive laboratory because policy constraints on cryptocurrency circulation have limited the institutional pathways through which speculative token economies can expand. Token-like markets have nonetheless evolved through the framing of NFTs as “digital collectibles,” frequently embedded in platform-controlled environments. These market developments sit within China’s broader digital industrial strategy, which has placed

Table 2
Source categories used in the structured synthesis and how they support the analysis

Source category	Ideas in this paper	How it supports the analysis
Peer-reviewed NFT/blockchain sustainability research	NFT emissions and carbon-debt studies; consensus-mechanism reviews	Establishes verification-layer emissions variability and protocol-level sustainability determinants
Infrastructure and data-center analyses	Data-center electricity demand reports; AI server and cooling/water-use studies	Anchors the infrastructure layer and clarifies why unit efficiency does not guarantee absolute impact reduction
Governance and standards literature	Standards-based metaverse governance proposals; UNESCO platform governance principles; EU institutional briefings	Supplies the accountability and auditability criteria used to evaluate sustainability claims
China-specific legal, policy, and compliance sources	Legal briefings on digital collectibles; blockchain-strategy think-tank reports; data-compliance and data-center policy reporting	Documents the regulatory-laboratory mechanisms used throughout Section 4 and the China-specific subsections of Sections 5 and 6

unusual emphasis on state-aligned infrastructure and standard-setting, linking platform governance, technological sovereignty, and sustainability objectives to a shared policy horizon [9–11].

This configuration matters because it highlights an often neglected proposition. Tokenization is not a binary technological condition but an institutional form that can be shaped by market design constraints, compliance architectures, and the availability of enforceable governance. In China, the separation between cryptocurrency markets and “digital collectibles” has contributed to tokenized ownership models that frequently operate under tighter rules governing payments, trading, and resale. In environmental terms, this does not automatically imply sustainability advantages. However, it does imply that throughput, speculative churn, and the scale dynamics of token markets can be structurally affected by governance, which is precisely why a China-oriented lens is analytically useful.

A second laboratory feature concerns China’s approach to blockchain development itself. Policy and strategy analyses emphasize that China’s ambitions have often favored state-guided infrastructure pathways and permissioned systems, with governance control and standards capacity treated as strategic assets rather than as incidental by-products [9, 10]. This orientation is relevant to the metaverse because immersive ecosystems depend on trust infrastructures, identity systems, compliance controls, and interoperability decisions, all of which can be shaped through standards and state–industry coordination.

This governance logic is strongly intertwined with China’s broader platform regulation environment. Research on China’s regulation of digital platforms emphasizes *ex ante* intervention, competition and consumer protection rationales, and the institutional capacity to shape platform conduct through policy tools rather than relying primarily on litigation or *ex post* enforcement [23]. At the same time, work on enforcement variation highlights that regulatory intensity is not uniform across contexts, indicating that governance outcomes depend on both formal rules and their operationalization [24].

China’s relevance also extends beyond tokenized markets and into the infrastructure layer that sustains immersive ecosystems. Metaverse systems, especially those coupled with AI-enabled content pipelines, rely on data-center provisioning, high-density compute, and intensive networking. The infrastructure problem therefore cannot be detached from national strategies and regulatory constraints that target data-center efficiency, energy sourcing, and compliance regimes. Authoritative global assessments

emphasize that data centers and data transmission networks are now an important component of electricity demand and are shaped by efficiency and cooling choices [16]. China adds a distinctive layer because infrastructure expansion is closely connected to industrial policy and because sustainability targets may be integrated into regulatory expectations for digital infrastructure development [26, 27].

A related dimension concerns data governance and compliance. Metaverse and NFT ecosystems intensify cross-border data questions because immersive systems generate persistent behavioral and biometric signals, while token markets introduce new forms of identity and transaction traceability. China’s evolving data-compliance environment, including stricter audits and cross-border rules, adds another layer to the governance landscape, shaping how platforms architect storage, identity systems, and disclosure practices [28].

The China laboratory also helps illustrate why “sustainability through gamified metrics” is not equivalent to sustainability through verifiable accounting. Platform-based sustainability initiatives, such as Ant Forest, have demonstrated that large-scale digital incentives can shape user behavior and translate environmental objectives into mass participation formats. Ant Forest has been widely discussed as an example of platform-enabled low-carbon behavioral mobilization and has received high-profile institutional recognition [18, 20].

Taken together, as summarized in Table 2, China’s regulatory and infrastructural configuration provides a useful laboratory for examining three coupled questions that are otherwise difficult to separate. The first is how tokenized ownership can be institutionalized under constraints that reshape market design and speculative dynamics [17, 23, 25]. The second is how state-aligned infrastructure strategy and standards capacity can shape the governance of emerging ecosystems, including the extent to which disclosure and accountability are feasible [9, 10]. The third is how sustainability targets interact with digital infrastructure expansion, affecting the environmental profile of immersive systems that depend on high-density compute and persistent networking [16, 26, 27].

5. Energy, Carbon, and Rebound Effects in Immersive and Tokenized Ecosystems

A credible sustainability assessment of metaverse and NFT-based ecosystems must begin with an explicit recognition that

their environmental profile is not dominated by a single component. It emerges from coupled layers of computation, network transmission, cloud and data-center provisioning, and verification architectures that support tokenized ownership. For this reason, sustainability claims that focus exclusively on “blockchain energy” risk understating infrastructure-driven impacts, while claims centered only on “efficient data centers” can ignore the behavioral and market incentives that scale total demand. What matters is the interaction between unit efficiencies and aggregate growth, particularly under rebound dynamics where lowering the per-unit cost of digital activity can increase the volume of activity enough to raise absolute energy and emissions [1, 3].

5.1. NFT verification architectures and emissions variability

NFT-related sustainability debates have often been anchored to the energy intensity of proof-of-work validation. This is understandable because proof-of-work systems link verification to computational competition and therefore to substantial electricity demand. However, the evidence base has shifted from generalized critique to more structured quantification. Empirical work has estimated greenhouse gas emissions associated with NFT activity and has framed the problem in terms of “carbon-debt” dynamics, emphasizing that impact is not merely a matter of single transactions but of ecosystem growth and cumulative demand [4]. This implies that even when per-transaction footprints decline, system-level impacts can remain material if trading volumes expand, if minting becomes frictionless, or if speculative churn accelerates.

Protocol choice is therefore a sustainability determinant rather than a technical footnote. Policy-oriented scholarship has argued that consensus mechanisms should be treated as subject to governance intervention because they embed different environmental and social risks and because protocol design influences the scale at which externalities are generated [12]. The shift of major public blockchains toward proof-of-stake systems is frequently discussed in sustainability debates as evidence that verification can be decoupled from the energy profile of proof-of-work competition. While exact magnitudes and boundary conditions differ across sources, the direction of effect is clear. Proof-of-stake designs remove the core incentive to consume electricity as a validation signal, which can substantially reduce operational energy demand relative to proof of work, even if other sources of impact remain, including hardware lifecycle effects and off-chain infrastructure [12–14].

China’s “digital collectibles” environment illustrates that token-like systems can be embedded in constrained market architectures where resale and payment pathways are restricted and compliance filters are stronger [17, 25]. This does not guarantee sustainability improvements, but it demonstrates that environmental outcomes are shaped by governance-mediated market form. A tokenized market that is optimized for high-frequency speculative turnover will generate different infrastructure demand than a tokenized market where trading is structurally throttled or where certain secondary-market dynamics are constrained.

5.2. The infrastructure layer as a scaling constraint

For metaverse ecosystems, particularly those designed around persistent presence and high fidelity, the infrastructure layer is increasingly decisive. Immersive environments generate continuous streams of data and require real-time rendering support, synchronization, storage, and content delivery. Even when

a device renders locally, metaverse platforms typically depend on cloud services for identity, content moderation, asset delivery, and increasingly for AI-enabled functions such as scene generation, recommendation, and automated governance. These dynamics bind metaverse growth to data-center electricity demand and to the energy profile of data transmission networks.

Authoritative energy system analysis has emphasized that data centers and data transmission networks are a significant and growing component of electricity demand, shaped by efficiency improvements, cooling strategies, and geographic power mix [16]. The sustainability implications are not linear. Efficiency can reduce the energy required per compute unit, but higher-density workloads, AI acceleration, and persistent connectivity can still raise total demand. Recent research on AI servers and environmental pathways underscores this concern by highlighting that net-zero trajectories may rely on uncertain mitigation measures if compute expansion outpaces grid decarbonization and water-stewardship capacity [17]. This is relevant to metaverse systems because AI functions increasingly sit inside metaverse pipelines, supporting synthetic content, moderation, and personalization.

Cooling and water use are part of the same sustainability equation. High-density compute generates heat, and cooling technology choices influence both electricity overhead and water consumption. Technical and policy-facing analyses describe a shift from traditional air cooling toward direct-to-chip and immersion cooling approaches, motivated by power density and efficiency constraints in AI-era data centers [16, 18, 19]. While such approaches can improve energy efficiency and reduce some operational overheads, they do not solve the demand problem if the compute footprint grows rapidly. Moreover, water consumption is increasingly recognized as a sustainability constraint for digital infrastructure expansion, adding a resource dimension that is often absent from popular “clean digital” narratives [19]. In other words, even when carbon intensity is reduced through renewable electricity, water scarcity and thermal management remain material constraints for scaling immersive and AI-intensive ecosystems.

China’s infrastructure governance further amplifies the relevance of this layer. Policy and compliance reporting around energy-efficient data centers suggests an increasing institutional push toward efficiency targets and sustainability-linked operational expectations [26, 27]. At the same time, China’s broader data-compliance regime and audit intensity can shape infrastructure architecture, including localization, redundancy, and cross-border transmission constraints that affect where and how energy burdens materialize [28]. These governance factors matter for sustainability because infrastructure design choices are not purely technical.

5.3. Lifecycle boundaries and the dematerialization problem

A recurring weakness in metaverse sustainability discourse is boundary selection. Narrow operational metrics can suggest progress while excluding upstream and downstream effects. A lifecycle-aware perspective complicates “dematerialization” narratives by emphasizing that digital ecosystems depend on device production, mineral extraction, manufacturing, and eventual e-waste streams, in addition to operational electricity and cooling. UNCTAD’s analysis of digitalization and environmental sustainability highlights precisely this displacement dynamic, where impacts migrate across supply chains and infrastructures rather than being eliminated [3]. The implication for metaverse

and NFT systems is that sustainability cannot be inferred from an assumed substitution effect. It must be assessed through explicit system boundaries and transparent accounting assumptions, including what counts as marginal metaverse-driven demand versus baseline digital infrastructure growth.

This boundary problem is compounded by the tendency for platforms to define sustainability through proxies that are not independently verifiable. Governance guidelines emphasizing transparency and accountability are therefore directly relevant to environmental claims. Without disclosure norms and auditable methodologies, claims about carbon neutrality or low footprint risk becoming reputational instruments rather than empirical statements [7]. The need for standards-based governance frameworks becomes stronger as metaverse ecosystems integrate tokenized markets because the legitimacy of these markets depends not only on user trust but also on the credibility of the ecosystem's sustainability narrative, particularly when digital assets are marketed as "future-oriented" or "clean" innovation [10, 25].

5.4. Rebound effects and the conditions for absolute impact reduction

Even if all unit-level efficiencies improve, absolute impact can increase through rebound mechanisms. Rebound is structurally likely in metaverse and NFT ecosystems because many design choices are oriented toward scaling engagement and transaction volume. When verification costs fall, minting becomes more accessible. When rendering becomes cheaper, fidelity increases. When bandwidth becomes faster, always-on presence becomes feasible. Each improvement reduces friction and therefore can increase total activity. The sustainability problem therefore becomes a question of whether governance and market design can limit the growth of energy-intensive behavior, or whether efficiency gains are simply reinvested into expansion [1].

The rebound question is not only theoretical. The empirical logic is visible in the way digital ecosystems evolve: lower costs, higher adoption, and new forms of consumption that were previously impractical. If immersive systems replace high-carbon activities at scale, net reductions are possible.

China's laboratory offers one way to observe how governance can shape rebound conditions. Market design constraints in tokenized ecosystems, including restrictions on secondary trading, can dampen speculative throughput and may reduce the intensity of transaction-driven scaling relative to fully permissionless environments [17, 25]. Infrastructure policy targets can also shape

rebound by imposing efficiency and compliance constraints on data-center expansion, though such constraints may shift demand geographically rather than reducing total demand if user-facing platforms continue to scale [26–28]. This suggests that rebound is not an inevitable outcome of technology alone. It is shaped by governance and by the institutional capacity to enforce constraints on market behavior and infrastructure provisioning.

5.5. Implications for sustainability evaluation in metaverse and NFT ecosystems

The evidence reviewed in this section points to the need for sustainability assessment to integrate verification architectures with infrastructure realities because metaverse and NFT ecosystems are jointly determined by tokenization and by compute provisioning. Credible sustainability claims also require lifecycle-aware boundaries and transparent accounting assumptions because operational metrics can be misleading if upstream impacts and displacement effects are excluded [9, 15]. Rebound dynamics must be treated as a core risk throughout because efficiency improvements can increase absolute demand unless governance, standards, and market design impose constraints or redirect incentives toward substitution rather than expansion [1, 6, 7].

Stated as discrete analytical propositions, the section's findings are: (P1) verification-layer efficiency gains (e.g., proof-of-stake adoption) reduce operational energy intensity but do not by themselves determine ecosystem-level impact because impact is co-determined by infrastructure provisioning; (P2) lifecycle boundary choices are not a neutral accounting detail but a determinant of whether a sustainability claim is verifiable because narrow operational boundaries can mask upstream device, grid, and water costs; and (P3) rebound dynamics are structurally likely under platform-growth incentives, such that absolute impact reduction requires governance-imposed constraints on throughput and scale rather than reliance on unit efficiency alone. Below is Table 3, which concludes the ecosystem layers, sustainability risks (that have been mentioned above), and the governance levers. It clarifies how different layers, risks, levers, and the relevant measurable indicators.

6. Governance Architecture, Standards, and Accountability

Sustainability in metaverse and NFT-based ecosystems cannot be treated as an external add-on to otherwise "neutral"

Table 3
Ecosystem layers, sustainability risks, and governance levers (synthesized from Sections 5 and 6)

Ecosystem layer	Sustainability risk	Governance lever	Indicative measurable indicator
Device and interface	Embodied carbon and e-waste from replacement cycles	Lifecycle disclosure requirements	Device replacement rate; embodied carbon per device
Cloud and data center	Rising absolute electricity/water demand despite efficiency gains	Energy-use-effectiveness targets; water-stewardship reporting	Power usage effectiveness/Water usage effectiveness; absolute electricity and water draw over time
Verification and market	Speculative throughput and minting volume driving demand	Resale/payment restrictions; consensus-mechanism mandates	Transaction/minting volume; secondary-market turnover rate
Governance and disclosure	Selective accounting and non-auditable "green" claims	Standardized boundary disclosure; independent auditability	Share of claims independently verified; audit frequency

technological systems. It is produced, stabilized, or undermined through governance choices that determine what is measurable, what is reportable, and what is enforceable. The problem is not simply that environmental impacts exist. It is that the impacts are distributed across layers and actors, while responsibility is often rhetorically centralized in a single element such as “the blockchain” or “the data center.” Governance becomes the mechanism that either aligns these layers into auditable accountability chains or leaves them fragmented, enabling selective disclosure and reputational sustainability claims that cannot be independently verified [3, 6].

A first governance challenge is the mismatch between ecosystem complexity and the simplicity of common policy responses. Metaverse systems combine identity and authentication, immersive interaction, market infrastructure for digital goods, moderation and safety functions, and cross-border data flows. NFTs add an additional governance burden because tokenized markets amplify disputes around consumer protection, fraud, and financial risk, while also producing environmental narratives that vary sharply across verification architectures and market designs [4, 12, 17, 25]. When governance approaches address only one component, they often fail to constrain the mechanisms that scale energy demand and externalities. This is why standards-based governance and platform accountability frameworks are central rather than peripheral to sustainability outcomes [8, 10, 25].

6.1. Standards-based governance and the problem of interoperability

Standards matter because metaverse ecosystems are rarely isolated. Even when platforms are centralized, they rely on interconnections across devices, software ecosystems, payment infrastructures, storage and identity systems, and content distribution networks. Interoperability therefore becomes both an economic objective and a governance risk. Without standards, interoperability tends to be replaced by platform enclosure, where a few large actors set rules in practice through market power. With standards, interoperability becomes feasible, but only if governance institutions coordinate rule-making, compliance, and enforcement.

The argument for technical-standards-led governance is developed clearly in work that proposes phased and standards-oriented approaches to metaverse governance, emphasizing that enforceable baselines require coordinated policy design rather than a reliance on voluntary self-regulation [25]. The value of this perspective for sustainability is that it treats measurement and reporting as governance artifacts. If sustainability metrics, boundary definitions, and disclosure duties are standardized across platforms, environmental claims become comparable and auditable. If they are not standardized, sustainability becomes a narrative competition, where actors select favorable boundaries and metrics to support marketing objectives rather than environmental accountability [3, 6, 7].

6.2. Platform accountability and auditability as environmental governance

A second challenge is the accountability gap typical of platformized ecosystems. Metaverse and NFT environments operate as multi-sided systems where users, creators, marketplaces, infrastructure providers, and regulators interact. Environmental costs are often generated at the infrastructure layer, while value

capture occurs at the platform and market layer. Governance must therefore create mechanisms that connect value capture to responsibility; otherwise, sustainability becomes an unfunded mandate in which no actor has both the incentive and the obligation to provide verifiable accounting.

UNESCO’s digital platform governance principles provide an actionable direction because they center transparency, checks and balances, and multi-stakeholder governance as prerequisites for legitimacy. While these guidelines are not written as climate policy, they translate directly into sustainability governance requirements in metaverse ecosystems. If platforms claim low environmental impact or carbon neutrality, accountability requires transparent methodologies, disclosure of boundary choices, and the possibility of independent verification rather than self-attestation. This is especially important where sustainability narratives are used to legitimize tokenized markets because NFT ecosystems have a well-documented tendency to oscillate between innovation rhetoric and reputational backlash, often without stable disclosure norms that can settle disputes empirically [4, 7, 12].

The European regulatory environment is frequently discussed in terms of stronger platform duties, including risk assessment and transparency obligations. The implication for metaverse and NFT systems is that accountability mechanisms originally designed for safety, consumer protection, and information integrity can be extended to environmental transparency when sustainability claims become part of platform market positioning. This extension is not automatic. It requires explicit governance choices that define environmental reporting as a duty and that specify auditability requirements.

6.3. China’s constrained tokenization and governance-by-design

China provides a distinctive laboratory for governance-by-design because tokenized markets have often evolved under constraints that reshape the very form of tokenization. Jurisdictional analyses describe how NFT-like products are frequently framed as “digital collectibles,” often embedded in platforms where payment rails, resale conditions, and compliance checks are more tightly controlled than in permissionless crypto markets [17, 25]. This configuration offers two governance insights relevant to sustainability.

Market design constraints can function as sustainability levers in practice by dampening speculative churn and limiting throughput, which can reduce the scaling of verification and marketplace activity even when tokenization persists. This does not guarantee a lower footprint because impacts can shift to other layers such as storage, content delivery, and platform compute. However, it demonstrates that governance can alter the growth trajectory that drives rebound effects and that tokenized ecosystems are not environmentally identical across jurisdictions simply because they share a token concept [1, 17, 25].

Constrained tokenization also tends to concentrate accountability within a smaller number of large platforms and infrastructure actors. Strategy and policy analyses of China’s blockchain trajectory emphasize state-guided infrastructure ambitions and governance control, including the preference for permissioned or semi-permissioned approaches that can support policy objectives around oversight and compliance [9, 10]. In principle, such concentration can make disclosure and enforcement more feasible. If a smaller set of actors control marketplaces and infrastructure, regulators can impose reporting requirements and efficiency targets more directly. In practice, this can also create transparency

limitations if independent auditing is not enabled or if disclosure remains internal. This duality makes China valuable analytically because it shows that “governability” and “transparency” are not identical.

China’s platform governance environment adds another layer. Research on China’s digital platform regulation emphasizes proactive intervention and an *ex ante* regulatory logic oriented toward competition, consumer protection, and risk containment [23]. At the same time, analyses of enforcement variation underscore that regulatory effects depend on operationalization, not only on the presence of rules [24]. Applied to sustainability, this suggests that ambitious efficiency targets or disclosure policies can produce uneven outcomes if enforcement differs across sectors, regions, or platform categories. For metaverse and NFT ecosystems, which can span entertainment, commerce, and quasi-financial markets, the governance challenge is precisely to avoid fragmented compliance that allows sustainability claims to persist in the absence of consistent verification.

Combined infrastructure governance and the evolving data-compliance regimes and stricter audits, these policies can influence how metaverse ecosystems architect data storage, localization, redundancy, and cross-border transmission [28]. This is not only a legal or sovereignty issue. It also shapes the distribution of infrastructure burdens and therefore the environmental profile of immersive platforms. Governance thus operates simultaneously at the market layer (tokenized goods), the platform layer (rules, moderation, identity), and the infrastructure layer (data centers, networks, compliance). Sustainability governance fails when these layers are regulated in isolation and when disclosures do not align with the actual architecture of the ecosystem [7, 9, 10, 16, 17, 26, 27].

6.4. Governance trade-offs and the credibility of sustainability claims

Across jurisdictions, governance choices create trade-offs that are directly relevant to sustainability credibility. Standards-driven interoperability can support measurement and comparability, but it can also accelerate adoption and usage, increasing total demand under rebound dynamics unless constraints are built into the ecosystem’s incentive structure [1, 6]. Platform accountability obligations can improve transparency and safety, but they can also increase compute demand through continuous monitoring and moderation workloads, which may raise infrastructure burdens if not accompanied by efficiency measures and lifecycle-aware accounting [8]. Constrained tokenization can reduce speculative throughput, but it can also shift activity toward platform-controlled infrastructures where independent verification is more difficult, creating a different form of legitimacy risk if sustainability claims cannot be externally audited [7, 9, 17, 25].

These trade-offs imply that governance must be evaluated not only by its capacity to impose rules but also by its capacity to create credible epistemic conditions for sustainability claims. In practical terms, standardized and disclosed system boundaries are needed to prevent claims based on opportunistic accounting [1, 3]. Reporting must also be auditable through independent verification channels rather than limited to self-reporting, especially where market incentives reward “green” branding [7, 21]. Addressing scale and rebound requires governance to align market incentives with sustainability constraints. Otherwise, efficiency improvements are likely to be absorbed into expansion rather than producing absolute impact reductions [15, 25].

7. Discussion and Implications for Sustainable Innovation

The analysis developed across the previous sections supports a core argument: Sustainability in metaverse and NFT-based ecosystems is not a property that can be “added” through messaging or marginal efficiency improvements. It is an outcome produced by coupled socio-technical layers and stabilized, if at all, through governance architectures that make environmental claims measurable, comparable, and enforceable. This discussion consolidates the evidence-driven findings on energy and infrastructure burdens with the governance mechanisms that shape market incentives, disclosure discipline, and the credibility of sustainability narratives. It also clarifies what “sustainable innovation” can plausibly mean in immersive and tokenized ecosystems when growth logic and rebound dynamics remain structurally strong [1, 3, 6, 7].

The findings reveal the limits of protocol-centered sustainability debates. The literature on NFT-related emissions demonstrates that verification architecture and transaction throughput matter and that the environmental controversy cannot be resolved by rhetorical claims alone [4]. Governance-oriented research further shows that consensus mechanisms and verification designs are policy-relevant because they embed externalities and create different sustainability profiles [12]. Yet the paper’s broader infrastructure analysis indicates that even a transition toward less energy-intensive verification does not eliminate sustainability risk when metaverse ecosystems scale through persistent presence, high-fidelity content, and AI-enabled pipelines that rely heavily on cloud and data-center provisioning [16, 17]. Sustainable innovation therefore cannot be defined narrowly through a single technical shift. It requires an integrated accounting logic that includes infrastructure, lifecycle boundaries, and behavioral scaling conditions; otherwise, “green claims” can remain true only inside artificially narrow boundaries [1, 3].

Measurement boundaries also shape sustainability outcomes and the credibility of environmental claims. Digital sustainability is repeatedly distorted by boundary selection, particularly when actors report operational metrics while excluding upstream device production, embodied carbon, and e-waste, or when they ignore displacement and rebound effects that convert efficiency gains into increased absolute demand [1, 3]. The metaverse intensifies this risk because it combines multiple high-impact layers, including continuous data transmission, high-density compute, and increasingly the integration of AI-driven generation and moderation functions. In this context, sustainable innovation becomes inseparable from methodological discipline. It requires explicit, standardized boundary definitions and transparent disclosure about what is being counted and what is being excluded. Without such discipline, the market is incentivized to optimize sustainability narratives rather than sustainability outcomes, a problem that is exacerbated when tokenized markets reward speculative attention and reputational signaling [4, 7].

Rebound remains a structural sustainability risk. The evidence base does not support an assumption that efficiency will translate into absolute reductions in impact. Rebound dynamics are plausible, and in platform economies they are often predictable. When costs fall and frictions are reduced, adoption expands, engagement grows, and new forms of consumption become viable. This dynamic applies to immersive ecosystems when rendering and bandwidth become cheaper and to tokenized markets when minting and trading become more accessible. The implication is that sustainable innovation must be evaluated

under conditions of scale, not merely under conditions of technical improvement. If governance does not impose constraints or reshape incentives toward substitution rather than additive consumption, the direction of change can be efficiency with rising absolute demand [1].

This is where China's regulatory laboratory clarifies a crucial mechanism. China illustrates that tokenization can persist in constrained forms that dampen speculative throughput and reshape market growth trajectories, even if such constraints do not automatically produce environmental benefits [17, 25]. The laboratory is analytically useful because it separates the technical possibility of tokenized ownership from the institutional form of token markets. It also shows that governance-by-design can be implemented through platform architectures, compliance filters, and restrictions on secondary trading, which can alter the scale conditions that drive rebound. At the same time, China also illustrates a countervailing risk: Concentrated platform control may increase governability but can limit independent verification, and sustainability claims remain vulnerable if disclosure is not externally auditable [7, 9, 10]. Sustainable innovation therefore cannot be reduced to "strong governance" in an abstract sense. It depends on the joint presence of enforceability and verifiability, and those two conditions do not always co-occur.

The governance tools available to address these problems differ across jurisdictions. The European trajectory, including the broader movement toward platform duties and transparency obligations, suggests that accountability infrastructures can be institutionalized and can provide a basis for extending disclosure requirements into environmental domains [21]. Standards-oriented governance proposals also emphasize that metaverse ecosystems require coordinated technical baselines and phased policy design to avoid fragmentation and weak self-regulation [6]. From a sustainable innovation perspective, these tools matter because they can reshape what platforms must disclose and what regulators can audit. They also enable comparability across platforms, which is essential for preventing sustainability narratives from becoming non-falsifiable branding. However, the discussion also indicates that governance itself can impose compute burdens through continuous monitoring and compliance functions. Sustainable innovation therefore requires a governance design that is sensitive to the operational costs of accountability and that seeks efficiency and proportionality in audit and disclosure mechanisms, rather than assuming that accountability is environmentally costless [8].

Infrastructure governance must also be treated as part of metaverse governance. Metaverse ecosystems depend on data-center capacity, cooling technologies, grid mix, and water stewardship. The evidence on data centers and AI server pathways highlights that energy and water pressures are likely to remain material and that mitigation depends on uncertain and unevenly distributed conditions. China's emphasis on energy-efficient data centers and policy-facing guidance on sustainability targets illustrates that infrastructure governance can be mobilized, at least in principle, as part of a broader digital industrial strategy [26, 27]. Yet data governance regimes and cross-border compliance constraints can also reshape architectural choices, potentially shifting burdens rather than reducing them [28]. This implies that sustainable innovation must treat infrastructure policy, platform governance, and market design as interdependent. If policy interventions improve data-center efficiency but platform incentives continue to drive engagement expansion, the net outcome may still be rising absolute demand.

Finally, the discussion clarifies the paper's contribution to sustainable innovation debates. The contribution is not a claim that metaverse and NFT ecosystems can be made sustainable through a single solution. It is a governance-informed ecosystem model that identifies where externalities are produced, why they scale, and what institutional mechanisms can transform sustainability from a rhetorical attribute into a measurable constraint. Sustainable innovation, under this model, requires credible disclosure regimes, standardized boundary definitions, and auditability structures aligned with the architecture of the ecosystem. It also requires that governance confront rebound dynamics by shaping incentives and constraining scale where necessary, rather than relying on per-unit efficiencies as a proxy for environmental progress [1, 3, 6, 7].

The next section concludes the paper by summarizing the core findings, acknowledging limitations, and outlining a research agenda focused on comparative governance, measurement standards, and the evolving infrastructure constraints that will shape the environmental feasibility of immersive and tokenized digital ecosystems [6–8, 21, 22].

8. Conclusion

This article has examined sustainability, governance, and energy trade-offs in metaverse and NFT-based digital ecosystems by treating these systems as layered socio-technical configurations rather than as isolated technologies. Across the analysis, a consistent conclusion emerges. Environmental impact is produced through the coupling of verification and market infrastructures with cloud provisioning, data-center expansion, network transmission, and device lifecycles. As a result, sustainability is not a stable attribute of "the metaverse" or "NFTs" in the abstract. It is an outcome that depends on architecture, market design, and governance capacity to impose transparent and auditable constraints on how these ecosystems scale [1, 3].

Empirical research has quantified emissions and carbon debt dynamics associated with NFT activity, showing that impacts are shaped by cumulative demand and market scale rather than by single transactions [4]. Policy-oriented scholarship reinforces that consensus mechanisms are not merely technical parameters but governance-relevant design choices that embed externalities and can be targeted through institutional intervention [12]. However, the broader infrastructure analysis suggests that verification is only one part of the sustainability equation. Metaverse systems are increasingly bound to data-center and AI server trajectories, and these infrastructures involve coupled electricity, water, and cooling constraints that can remain material even when per-unit efficiencies improve [16, 18–20].

The second conclusion concerns the centrality of measurement boundaries and rebound dynamics. Digital sustainability narratives often assume that virtual substitution implies dematerialization. However, policy and research on digitalization and environmental sustainability emphasize that impacts can shift upstream to infrastructure, devices, and supply chains, and that efficiency improvements can coexist with rising absolute emissions when adoption expands rapidly [1, 6]. Metaverse and tokenized ecosystems are especially vulnerable to rebound because platform growth incentives reward persistence, engagement, and market expansion. Under these conditions, sustainable innovation cannot be equated with unit efficiency alone. It must be evaluated under conditions of scale, and it requires governance mechanisms capable of shaping incentives so that substitution dominates additive consumption [1].

Regarding the last conclusion, it is that governance architecture is the operational bridge between sustainability discourse and measurable outcomes. Standards-based approaches to metaverse governance emphasize that enforceable baselines depend on coordination, phased policy design, and institutional capacity rather than voluntary self-regulation [6]. Accountability frameworks, including UNESCO's principles for digital platform governance, reinforce that transparency, checks and balances, and multi-stakeholder oversight are prerequisites for legitimate claims in high-impact platform ecosystems [7]. The European governance trajectory illustrates how platform duties and transparency expectations can provide institutional tools that may be extended to environmental disclosure. It is also about auditability, even when sustainability is not the primary regulatory target [21]. Governance is a sustainability determinant because it shapes disclosure discipline, comparability, and the possibility of independent verification.

China has been used as a regulatory laboratory to clarify mechanisms that are otherwise difficult to separate. China demonstrates that tokenized ownership can persist under constrained market designs where platform-mediated architectures and compliance filters shape throughput, resale conditions, and market expansion [17, 25]. This illustrates that tokenized ecosystems are not environmentally identical across jurisdictions because market form is governance-mediated. China also foregrounds a broader strategy in which blockchain development and digital infrastructure are often framed through state-aligned governance logics and standards capacity, which can increase the feasibility of enforceable constraints while also raising questions about transparency and independent verification [9, 10]. The laboratory therefore clarifies a key trade-off. Strong governability can increase the capacity to impose rules, but credibility of sustainability claims depends equally on auditability and externally verifiable disclosure [7, 9, 10, 24, 30].

The article has limitations that define a research agenda. It does not offer direct measurement of platform-specific energy consumption. Instead, it identifies where impacts are structurally produced and which governance levers can make measurement, comparability, and enforcement feasible across ecosystems [6–8]. Future research would benefit from comparative empirical studies that combine platform-level infrastructure data with standardized lifecycle boundaries. Finally, because metaverse systems are increasingly entangled with AI workloads and accelerated computing, research on net-zero pathways for digital infrastructure and their constraints around electricity, cooling, and water will remain foundational for any credible sustainability roadmap in immersive and tokenized ecosystems [19].

The practical implication is straightforward. Sustainable innovation in metaverse and NFT-based ecosystems is possible only insofar as governance transforms sustainability from a rhetorical attribute into an operational constraint. This requires explicit boundary definitions, standardized disclosure, and auditability aligned with the ecosystem's actual architecture.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Vincenzo de Masi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Supervision, Project administration. **Ernestina Xinyi Zhu:** Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration.

References

- [1] Callegari, B., Misganaw, B. A., & Bagherzadeh, M. (2024). Paved with good intentions: From digitalization to carbon neutrality. *Journal of Environmental Management*, 370, 122956. <https://doi.org/10.1016/j.jenvman.2024.122956>
- [2] Kshetri, N., & Dwivedi, Y. K. (2023). Pollution-reducing and pollution-generating effects of the metaverse. *International Journal of Information Management*, 69, 102620. <https://doi.org/10.1016/j.ijinfomgt.2023.102620>
- [3] Beaumier, G., & Gjesvik, L. (2025). Digital governance in a rubber band: Structural constraints in governing a global digital economy. *Global Studies Quarterly*, 5(2), ksaf043. <https://doi.org/10.1093/isagsq/ksaf043>
- [4] Lal, A., & You, F. (2023). Climate concerns and the future of nonfungible tokens: Leveraging environmental benefits of the Ethereum Merge. *Proceedings of the National Academy of Sciences*, 120(29), e2303109120. <https://doi.org/10.1073/pnas.2303109120>
- [5] Li, F., & Diao, Z. (2025). The impact of digital infrastructure on the synergistic effects of urban pollution and carbon reduction: Empirical evidence from China. *Frontiers in Environmental Science*, 13, 1453151. <https://doi.org/10.3389/fenvs.2025.1453151>
- [6] Yañez-Barnuevo, M. (2025). *Data centers and water consumption*. Environmental and Energy Study Institute. Retrieved from: <https://www.eesi.org/articles/view/data-centers-and-water-consumption>
- [7] UNESCO. (2023). *Guidelines for the governance of digital platforms*. Retrieved from: <https://www.unesco.org/en/internet-trust/guidelines>
- [8] Xynogalas, V., & Leiser, M. R. (2024). The Metaverse: Searching for compliance with the General Data Protection Regulation. *International Data Privacy Law*, 14(2), 89–105. <https://doi.org/10.1093/idpl/ipae004>
- [9] Xu, J., Guo, D., Hu, Y., & Yuan, Y. (2024). Blockchain as a breakthrough in technological innovation: Policy narratives and future imaginaries of China's strategies. *Journal of Broadcasting & Electronic Media*, 68(5), 714–735. <https://doi.org/10.1080/08838151.2024.2398618>
- [10] Sigley, G., & Powell, W. (2023). Governing the digital economy: An exploration of blockchains with Chinese characteristics. *Journal of Contemporary Asia*, 53(4), 648–667. <https://doi.org/10.1080/00472336.2022.2093774>
- [11] McKnight, S., Kenney, M., & Breznitz, D. (2023). Regulating the platform giants: Building and governing China's online economy. *Policy & Internet*, 15(2), 243–265. <https://doi.org/10.1002/poi.336>

- [12] Truby, J., Brown, R. D., Dahdal, A., & Ibrahim, I. (2022). Blockchain, climate damage, and death: Policy interventions to reduce the carbon emissions, mortality, and net-zero implications of non-fungible tokens and Bitcoin. *Energy Research & Social Science*, 88, 102499. <https://doi.org/10.1016/j.erss.2022.102499>
- [13] Bada, A. O., Damianou, A., Angelopoulos, C. M., & Katos, V. (2021). Towards a green blockchain: A review of consensus mechanisms and their energy consumption. In *2021 17th International Conference on Distributed Computing in Sensor Systems*, 503–511. <https://doi.org/10.1109/DCOSS52077.2021.00083>
- [14] Sandberg, K. (2023). *Web3 and sustainability: How we can reduce the climate impact of blockchains, how blockchains can help reduce our own*. The Linux Foundation. Retrieved from: <https://project.linuxfoundation.org/hubfs/LF%20Research/Intel%20Web3%20and%20Sustainability%20-%20Report.pdf>
- [15] Doshi, A. R., & Schmidt, W. (2024). Soft governance across digital platforms using transparency. *Strategy Science*, 9(2), 185–204. <https://doi.org/10.1287/stsc.2023.0006>
- [16] Al Kez, D., Foley, A. M., Hasan Wong, F. W. B. M., Dolfi, A., & Srinivasan, G. (2025). AI-driven cooling technologies for high-performance data centres: State-of-the-art review and future directions. *Sustainable Energy Technologies and Assessments*, 82, 104511. <https://doi.org/10.1016/j.seta.2025.104511>
- [17] He, T., & Zhang, H. (2024). Copyright, platforms and NFT digital collections: Exploring the proper regulatory mode in China. *Journal of Intellectual Property Law & Practice*, 19(1), 18–31. <https://doi.org/10.1093/jiplp/jpad100>
- [18] Li, X., Zhao, Z., Jiang, X., Chen, Y., & He, R. (2025). A review on AI-driven optimization of data center energy efficiency and thermal management. *International Journal of Applied Science*, 8(3), p108. <https://doi.org/10.30560/ijas.v8n3p108>
- [19] Yang, L. (2023). Recommendations for metaverse governance based on technical standards. *Humanities and Social Sciences Communications*, 10(1), 253. <https://doi.org/10.1057/s41599-023-01750-7>
- [20] Cai, S., & Gou, Z. (2026). Towards energy-efficient data centers: A comprehensive review of passive and active cooling strategies. *Energy and Built Environment*, 7(1), 206–226. <https://doi.org/10.1016/j.enbenv.2024.08.009>
- [21] Lopez-Tarruella, A., & Rodríguez de las Heras Ballell, T. (2025). A European regulatory framework for the Metaverse. *MetaverseUA Chair Research Paper #1. SSRN*. <https://doi.org/10.2139/ssrn.5024023>
- [22] Zhang, C., & Wang, L. (2025). Virtual worlds, real politics: A cross-national comparative study of Metaverse policy approaches. *Politics and Governance*, 13, 10239. <https://doi.org/10.17645/pag.10239>
- [23] Sakharov, A., & Shelepov, A. (2024). China's digital platforms regulation policy. *International Organisations Research Journal*, 19(2), 145–160. <https://doi.org/10.17323/1996-7845-2024-02-08>
- [24] Zhang, J. D. (2026). Variations in the enforcement of China's platform regulation. *Socio-Economic Review*, 24(2), 667–694. <https://doi.org/10.1093/ser/mwaf076>
- [25] Xiao, B. (2022). Copyright law and non-fungible tokens: Experience from China. *International Journal of Law and Information Technology*, 30(4), 444–471. <https://doi.org/10.1093/ijlit/eaad007>
- [26] Li, G., Sun, Z., Wang, Q., Wang, S., Huang, K., Zhao, N., . . . , & Zhu, Z. (2023). China's green data center development: Policies and carbon reduction technology path. *Environmental Research*, 231, 116248. <https://doi.org/10.1016/j.envres.2023.116248>
- [27] The Legal Wire. (2025). *China issues new energy efficiency rules for data centres which may affect advanced chips*. Retrieved from: <https://thelegalwire.ai/china-issues-new-energy-efficiency-rules-for-data-centres-which-may-affect-advanced-chips/>
- [28] Li, L. (2025). Data sovereignty and national security: Governance challenges and pathways in the digital age. *Global Review of Humanities, Arts, and Society*, 1(1), 49–58. <https://doi.org/10.63802/grhas.v1.i1.7>
- [29] Ghorpade, S., Lall, A. B., Gupta, A., Rai, S. P., & Shetty, M. (2025). Blockchain based carbon footprint verification and management. *International Journal of Environmental Sciences*, 11(21s), 2156–2165.
- [30] de Masi, V., Di, Q., Li, S., & Song, Y. (2025). Sustainable game design in China: Pioneering practices and future directions. In P. Prax, C. Whittle, & T. York (Eds.), *The game needs to change: Towards sustainable game design* (1st ed., pp. 144–153). CRC Press. <https://doi.org/10.1201/9781003512400-16>

How to Cite: de Masi, V., & Zhu, E. X. (2026). Metaverse and NFT-Based Digital Ecosystems: Sustainability, Governance, and Energy Trade-Offs. *FinTech and Sustainable Innovation*. <https://doi.org/10.47852/bonviewFSI62029211>