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Post-Merge Carbon Footprint Analysis and Sustainability in the NFT Art Market

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Abstract: The market for non-fungible token (NFT) art is expected to reach USD 44.2 billion in 2021 and increase by 67.57 percent in 2022, revolutionizing the relationship between artists, collectors, and investors. Despite this, concerns regarding the environmental impact of blockchain technology's high energy consumption persist. NFT art transactions will continue to generate significant carbon emissions after Ethereum's "Merge" to a Proof-of-Stake (PoS) system in September 2022, rendering many low-carbon solutions obsolete and necessitating further research into post-Merge alternatives. This study identifies solutions in the NFT art market, such as carbon neutrality, lazy minting, alternative consensus mechanisms, Layer 2 solutions and policy interventions. Carbon neutrality is achieved through investments in renewable energy or carbon credits to mitigate emissions generated by NFT art transactions. Lazy minting reduces energy consumption by postponing the creation of NFT art until a buyer is secured. In the NFT art ecosystem, alternative consensus mechanisms such as Proof of Authority (PoA) and Proof of Spacetime (PoST) reduce energy consumption. By offloading transactions from the primary blockchain, Layer 2 solutions enhance scalability and reduce energy consumption. Carbon taxes and energy consumption levies are examples of policy interventions that promote cleaner energy sources in the NFT art market. This study will explore the role of artists, collectors, galleries, and other significant players in encouraging environmentally sustainable practices in the NFT art market. In addition, it will investigate the effect of prominent NFT art sales on carbon emissions and the adoption of eco-friendly alternatives. By integrating and optimizing current carbon reduction strategies, the NFT art market can continue to flourish while reducing its environmental impact. The study emphasizes the significance of implementing a comprehensive strategy that incorporates multiple solutions that are tailored to the specific challenges of the NFT art market.

Keywords: non-fungible tokens; NFT art market; Ethereum Merge; carbon neutrality; sustainable development

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1. Non-Fungible Tokens (NFTs) and the NFT Art Market

1.1. Non-Fungible Tokens (NFTs)

The non-fungible token (NFT) represents a distinct category within the realm of digital assets, and its surge in prominence has propelled discussions on its sustainable development. NFTs are the digital ownership and authenticity certificates for digital or physical objects. When an NFT is minted, a unique entry is created in the blockchain ledger to identify it, and when it is sold, its transfer is likewise recorded to keep the ownership public. NFTs can be used in various areas of life and for almost everything that can be stored (Kumar 2022). NFT art distinguishes itself from other cryptocurrencies not only due to its intrinsic non-substitutable nature (Dowling 2021), but also because it serves as a verifiable proof of provenance and a novel sales mechanism in the art domain.

The NFT market encompasses various sectors such as art, collectibles, games, and the metaverse. However, the diversity is not just in these sectors but in how NFTs are utilized within them. For instance, a single NFT can serve as a valuable art collectible, perhaps auctionable on esteemed platforms like Sotheby's, while also offering "utility" features

such as special access to events or as a digital certificate of provenance. The layered utility of NFTs not only exemplifies their dynamism but also lends them a multifaceted role in the worlds of art, gaming, and beyond. An item of NFT art is a unique cryptocurrency token that may take the shape of virtually anything digital, including artwork, GIFs, and even the first tweet by Twitter CEO Jack Dorsey. Even though NFT art accounts for only 10% of the entire NFT market, it often becomes the center of discussions due to its transformative implications for the conventional art world (Nadini et al. 2021). The discourse distinguishing art from collectibles is pivotal, as it can mold market perceptions and valuations. The NFT art market, a significant subset of the broader NFT market, centers on the creation, trade, and collection of digital artworks that are authenticated via blockchain technology.

Most of the art-related NFTs operate on the Ethereum blockchain. Platforms like OpenSea, an aggregator, lets consumers trade NFTs from multiple marketplaces. However, Nifty Gateway is known for its exclusive artist collaborations and drops (Chang 2023). SuperRare is a curated portal for premium digital art. Each platform has a different user experience, accessibility, and collection of artworks, demonstrating the diversity and versatility of Ethereum-based NFT art. Ethereum's share of NFTs declined from 95% in 2021 to 80% in 2022 (Canny 2022). Through its smart contracts and decentralized applications, the second-largest blockchain supports a large developer and user community (Dapps). Multiple ecosystems for NFTs have emerged on the Ethereum blockchain (Bhalla 2022). In September 2022, Ethereum made notable alterations to its protocols, reducing its greenhouse gas emissions. Nevertheless, Ethereum, along with various other leading cryptocurrencies, still employs energy-intensive processes, which continue to produce substantial greenhouse gas emissions. This underscores the ongoing environmental concerns associated with blockchain technology.

1.2. The NFT Art Market

The NFT art market, while a recent phenomenon, has experienced dramatic and substantial growth, especially in the years between 2017 (Deloitte 2017) to 2022. The early years from 2017–2020 marked the foundational phase of the NFT art market. The Whitney Museum's groundbreaking cooperation with Kevin and Jennifer McCoy was one such event. In 2019, their avant-garde project "Public Key/Private Key" critically examined museum art ownership paradigms and donor–museum relationships. By intertwining it with blockchain technology, they extended its market life and allowed contributors to participate in an ongoing art ownership tapestry (Whitney Museum 2019).

According to the NFT Art Report 2018–2019, the NFT art segment witnessed a massive growth of over 114%, with the total traded volume escalating from USD 260,290 in 2018 to USD 559,403 in 2019. The number of artworks traded increased from 2146 in 2018 to 32,084 in 2019 (NonFungible Report 2018–2019 2019). In 2020, the NFT art segment made significant strides. The dollar value traded reached an impressive USD 20,156,934, showcasing the resilience and adaptability of the market (NonFungible Report 2020 2020). In the face of the epidemic and lockdowns, many artists turned to NFTs for revenue and artistic expression.

Fast-forwarding to 2021–2022, the market saw a significant uptick in both attention and valuation. A study by Chainalysis (2022) indicated that the NFT art market number of transactions increased rapidly, with the average transaction value topping USD 20,000. The value of transactions involving digital collectibles and other forms of NFTs reached USD 44.2 billion in 2021 (NonFungible Report 2022 2022). In terms of the total number of transactions, the number of NFT purchases reached 101 million in 2022, representing a rise of 67.57% from the previous year's total (DappRadar 2023).

In 2022, the NFT art market generated an organic trading volume of around USD 24.7 billion across blockchain platforms and marketplaces, a modest decrease from the USD 25.1 billion in 2021, when the NFT art market activity peaked (Hayward 2023). Notably, the market saw dramatic fluctuations throughout the year. NFT sales peaked at USD 12.6 billion in January 2022 but experienced a staggering drop, totaling just over USD 1 billion by June 2022, a clear indication of the market's volatility (Milmo 2022). By October 2022, sales had plummeted by over 90% in almost every category, from volume to price, compared to the previous year's metrics (Parisi 2022). Despite these hurdles, the market showed signs of a post-crash recovery. Despite diversifying across platforms and blockchains in 2023, the NFT market has continued to grow (Gherghelas 2023).

The market's rise was driven by HNW collectors. They invested heavily in digital art, particularly NFTs. HNW collectors spent USD 46,000 on art-related NFTs in 2022, with 12% spending above USD 1 million (Art Basel 2022). This continuous rise and high-net-worth collectors' popularity is suggestive of the NFT art market's future.

In essence, the foundation of the NFT art market was created between 2017 and 2020, and it grew rapidly from 2021 to 2022. However, artists were among the first to worry about Proof-of-work NFTs' environmental impact. Their proactive actions show how art transforms this ecology. Evident are the market's dynamism, adaptability, and growth potential. However, as we explore the complexities of this topic, the fundamental environmental concerns, especially the increased carbon emissions caused by mining and transactions, remain of the uttermost importance. As the market for NFTs continues to expand and diversify, a comprehensive comprehension of its environmental impact becomes essential; this will be the focus of the following chapter.

2. The Carbon Footprint of NFTs

The NFT art market's expansion has increased carbon emissions from mining and transactions, contributing to climate change and environmental degradation. The Ethereum merged on 15 September 2022, planned to switch from Proof-of-Work mining to a Proof-of-Stake system. However, NFT carbon emissions remain a concern. Therefore, carbon profiles of non-financial transactions must be studied and monitored to reduce their environmental impact.

In the vast NFT market, the art section shows intriguing sales value changes over time. From April 2021 to July 2023, NFT art sales had highs and lows. On 15 April 2021, a 30-day sales review revealed a figure of USD 78 million. This sum reached about USD 881 million by 15 September 2021. However, sales tapered off, reaching USD 14 million on 15 July 2023, which encompassed the 30-day period (Statista 2023).

Given that art NFTs represent 10% of the entire market, as established earlier (Nadini et al. 2021), it is crucial to take this figure into account when assessing the carbon footprint of NFT art. To offer a well-rounded perspective on its environmental impact, I will incorporate this proportion while examining the broader NFT ecosystem.

The carbon footprint is a measure of the exclusive total amount of carbon dioxide emission that is directly and indirectly caused by an activity or that is accumulated over the life stages of a product (Wiedmann and Minx 2007). The greenhouse gas emissions caused by the energy used in the production, transfer, and blockchain storage of NFTs are included in their carbon impact. This includes the equipment used to access and store NFTs as well as the energy consumption of NFT mining.

The NFT art market's rising popularity increases its environmental impact, even though bitcoin trading and games also contribute to global carbon emissions. Due to its rapid growth and rising social prominence, this industry offers a unique chance to examine its environmental impacts. Thus, studying the NFT art market's carbon footprint is both a scientific and sociocultural approach to promote sustainability. This chapter will examine NFT carbon emissions under both Proof-of-Work and Proof-of-Stake techniques to analyze this emergent digital art form's ecological footprint.

2.1. Carbon Emission of NFTs in a Proof-of-Work Mechanism

2.1.1. Ethereum and Its PoW Consensus

Ethereum previously employed Proof-of-Work (PoW) consensus processes. The creation of an NFT, known as "mining", requires computing power to solve complex mathematical problems, which requires a significant amount of energy. PoW is like a problem-solving contest where the winner gets a block as a reward. The greater the number of problem-solving attempts, the greater the likelihood of success. After each newly created block, the procedure is repeated endlessly. Before "The Merge", on 15 September 2022, Ethereum used a Proof-of-Work (PoW) consensus algorithm, which required 900 billion calculations per second for transaction validation (*Ethereum Is Ditching Miners and Merging to a Proof-of-Stake System: Here's Why | CBC News* n.d.). This PoW process required powerful mining equipment and was energy-intensive. With "The Merge", the Ethereum mainnet merged with the Beacon Chain, a proof-of-stake blockchain, eliminating the need for energy-intensive mining (*The Merge | ethereum.org* 2023).

As the landscape of blockchain technology evolves, the PoW mechanism has undeniably become a focal point of environmental discourse. Before Ethereum's notable transition to the Proof-of-Stake (PoS) model in August 2022, it was estimated that each NFT transaction under the PoW mechanism contributed a significant 48 kg of CO_2 emissions (Akten 2022). In 2022, 101 million NFTs were sold (DappRadar 2023), resulting in 4848 million kilograms of CO_2 emissions. This quantity is about 0.004848 gigatonnes of CO_2 in the widely recognized measure. To understand the environmental impact of this, imagine a green canopy of 150–220 million trees, depending on their carbon sequestration[1] capacity (Encon 2023). While Ethereum's switch to PoS reduces its carbon footprint, blockchain technology's environmental issues are significant, especially for systems that rely on PoW.

2.1.2. Bitcoin and Ordinals: The New Wave of NFTs

On the contrary, even as Ethereum transitioned toward the more environmentally-conscious Proof-of-Stake (PoS) mechanism. The use of ordinal NFTs, introduced to the Bitcoin mainnet by developer Casey Rodarmor on 20 January 2023, is a revolutionary method to NFTs (Chainlink 2023). These gained popularity quickly, setting daily registration records in April 2023 (Chainlink 2023). Ordinals encode all their data onto the Bitcoin blockchain, eliminating the requirement for external data sources (Larson 2023). Additionally, where most NFTs embed creator royalties, Ordinals deviate from this standard practice (Larson 2023).

However, Bitcoin's breakthrough adoption of Ordinals is still based on the PoW process, which has severe environmental costs. As the world's leading blockchain, Bitcoin's energy usage is massive, frequently equal to that of whole nations. In August 2022, Bitcoin's energy consumption was estimated as 60–77% of the global cryptocurrency-related electricity demand (Larson 2023).

Finally, NFTs' importance as revolutionary digital assets necessitates a rigorous assessment of their environmental impact. Given the substantial environmental dangers involved with their creation and transaction, especially within the PoW consensus framework, the sector must move to more sustainable alternatives. Technology is supposed to bring greener methods to the NFT industry, allowing it to thrive without harming the environment.

2.2. Carbon Emission of NFT Art in a Proof-of-Stake Mechanism

Ethereum's shift from a PoW to a PoS system emerged from the strategic foresight to amplify energy efficiency and curtail carbon emissions. While NFT art's ecological concerns were not the sole catalyst, they undeniably expedited this transition. With "The Merge", Ethereum veered away from exhaustive mining, using staked ETH to bolster its network. The PoS system does not incentivize block generation with computational power, and which machines construct the next block of the blockchain depends on their wealth. PoS leverages game theory to reach consensus, incentivizing users to stake a percentage of their native currency to validate NFT art transactions. The system uses a combination of

factors such as staking age, randomization, and node wealth to determine the next block's validator (Binance Academy 2018). The staking technique simply needs a device with sufficient storage and an internet connection, not computational capability. As a result of this modification, there is no longer a network of energy-intensive mining machines competing to produce the next block for the underlying blockchain, which greatly reduces carbon emissions; by at least 99.84% (Digiconomist 2023).

As illustrated in Figure 1, Ethereum's shift to a PoS system in September 2022 led to a marked reduction in carbon emissions. The annualized carbon footprints for Ethereum using PoS diminished to 0.01 TWh and 0.01 Mt CO_2, showcasing its progressive approach to sustainability within the realm of blockchain technologies.

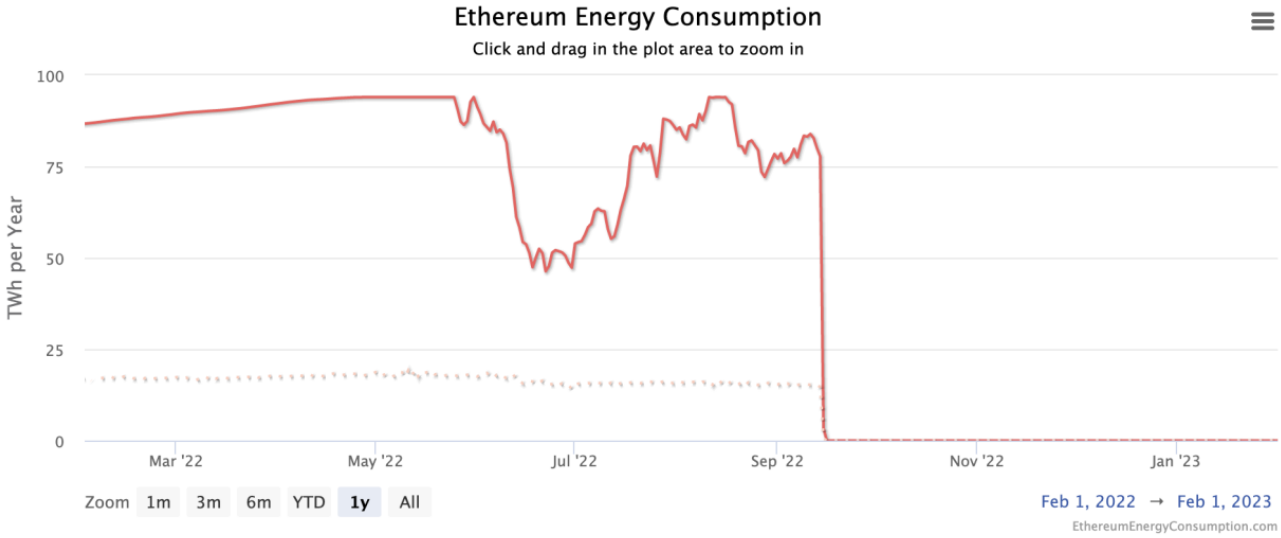

Figure 1. Ethereum energy consumption from 1 February 2022–1 February 2023. ***Note.*** The data is from (Digiconomist 2023). *Ethereum Energy Consumption Index*. Retrieved 1 February 2023, from https://digiconomist.net/ethereum-energy-consumption/. Copyright 2023 Digiconomist.

The data of energy consumption of Mastercard transactions are from *MasterCard USA | A Global Payment Technology Solutions Company*. (MasterCard USA 2019). Retrieved 9 February 2023, from https://www.mastercard.us/content/dam/mccom/global/aboutus/Sustainability/mastercard-sustainability-report-2017.pdf. Copyright 2019 by Mastercard.

The underlying blockchain technology replicates data and operations across thousands of machines, thereby increasing data redundancy and the energy expenses associated with maintaining multiple copies (De Vries 2023). Therefore, the Ethereum network may continue to be comparatively less energy-efficient than centralized alternatives. Figure 2 illustrates that a single Ethereum transaction incurs an energy footprint of 0.04 kWh and emits 0.02 kg CO_2. On the other hand, the Mastercard digital transaction system, emblematic of global digital payment infrastructures, consumes just 0.0007 kWh per transaction (MasterCard USA 2019). MasterCard transactions equal 57 Ethereum transaction footprints. Even though Ethereum has shifted to a PoS model, it is essential that policies and actions limit carbon emissions in order to ensure the sustainable development of the NFT art market.

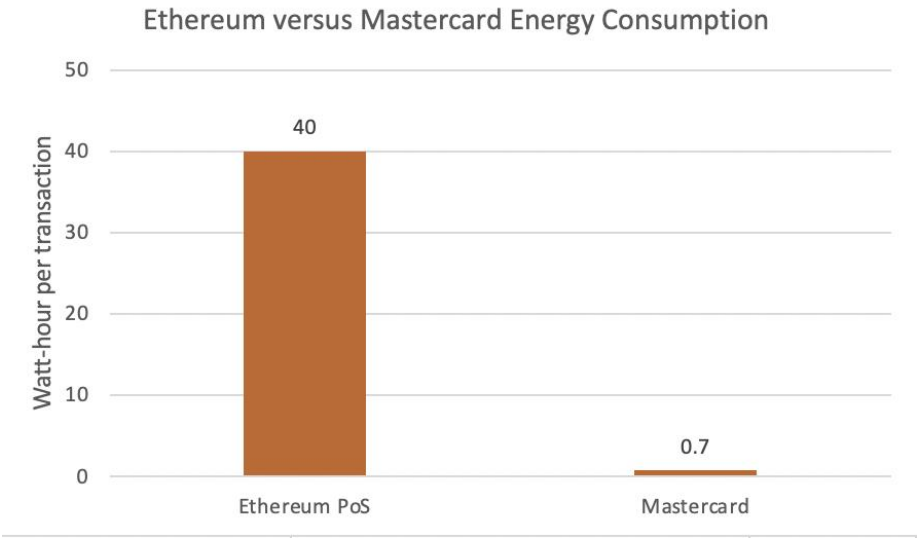

Figure 2. Energy consumption per transaction of PoS Ethereum and Mastercard. ***Note.*** The data on the Ethereum PoS mechanism is from Digiconomist (2023). *Ethereum Energy Consumption Index*. Retrieved 1 February 2023, from https://digiconomist.net/ethereum-energy-consumption/. Copyright 2023 by Digiconomist.

3. Solutions to Reduce NFT Art Carbon Emissions after the Merge

The increase in carbon emissions from NFT art transactions, which is predominantly attributable to the energy-intensive mining process in blockchain technology, is becoming a major cause for concern. Despite Ethereum's transition to a Proof-of-Stake (PoS) system, this concern persists, necessitating the study of additional strategies to reduce the carbon footprint of NFT art transactions. This occurs for three main reasons:

Primarily, the NFT art sector, despite its fluctuating market demand, presents environmental challenges. Due to its blockchain technology foundation, it has environmental implications. Beyond its revolutionary digital presence and commercial possibilities, NFT art represents the digitalization and democratization of art ownership. NFT art is transformative, even with variable demand, thus it is important to be proactive about its environmental impact. Establishing a durable foundation for a creative medium that can change cultural narratives is more important than business dynamics.

Secondly, even though Ethereum's transition to PoS reduced carbon emissions, it may be less energy-efficient than centralized alternatives. A single Ethereum transaction, often required for the purchase or sale of NFT art, is still quite energy-consuming. Consequently, the carbon emissions from NFT art transactions are still substantial and cannot be disregarded.

Thirdly, the NFT art realm demands environmental mitigation strategies that are as avant-garde as the art it represents. With the NFT art market being an ever-evolving entity, previous assessments might lack relevance in today's context. There is a need for innovative NFT art environmental mitigation strategies across consensus mechanisms. After all, art has always been a reflection of society, and in an age defined by environmental concerns, NFT art must mirror these values. Therefore, it is necessary to explore a variety of strategies to reduce the environmental impact of NFT art on the ecosystem.

3.1. Carbon Neutrality to Offset Carbon Emissions

Carbon neutrality might reduce NFT art's carbon footprint, benefiting creators, buyers, and platforms. Being carbon neutral is reducing emissions or buying carbon credits to offset them (*What's the Difference between Carbon Negative and Carbon Neutral?* 2020). It is expected to have no overall impact on the amount of greenhouse gases over the long term. Carbon neutrality is being achieved within the NFT art ecosystem through the use of

renewable energy or carbon-sequestering tokens and the mitigation of carbon emissions through carbon offsets.

3.1.1. Carbon Offsetting

Carbon offsetting involves either the removal of CO_2 from the atmosphere through the use of forestry or wind fields or the reduction in CO_2 emissions by other businesses or individuals (Hyams and Fawcett 2013). Regrettably, this approach may not be viable due to its considerable expense, which can ultimately negate the offset's advantages. For example, consider the renowned NFT marketplace, SuperRare. This has been proactive in addressing the environmental concerns associated with NFTs. It purchased offsets to counteract its carbon footprint. In addition to the works that artists have created, some NFT art organizations, such as ArtStation, have swiftly canceled the launch of their NFT art platform (ArtStation Magazine 2021). Critics cited the substantial energy consumption and carbon emissions associated with NFT blockchain transactions, prompting ArtStation to recognize the environmental implications and delay its plans. (Hayward 2021). Significantly, NFT platforms like KodaDot (*KodaDot About* n.d.) and Voice (Fish 2021), claim to be carbon-neutral. Therefore, although carbon offsetting provides a potential solution to the environmental impact of NFT art, it is not the only method being investigated. The industry is continually innovating and exploring new strategies. Certain blockchain-based tokens have been introduced.

3.1.2. Blending Art and Ecology: Carbon-Offset Innovations in NFTs

Building upon the framework of the carbon-offsetting mechanisms discussed in Section 3.1.1, it is imperative to explore innovations specifically engineered for NFT art. While the overall carbon neutrality strategies provide valuable insights, the emergence of art-specific solutions such as Carbon Collectible NFTs (CCNFTs) is adding a new dimension to how the art industry can address its ecological impact.

Moving beyond the conventional use of renewable energy for carbon mitigation, there has been an innovative foray into the deployment of specialized tokens, such as Carbon Collectible NFTs (CCNFTs), which leverage carbon credits to offset the ecological impact of NFT art transactions. CCNFTs are new NFTs that offset carbon emissions from minting and trading by providing digital rights to one hectare of mature forest land and carbon sequestration based on satellite pictures (Kumar 2022). The buyer can purchase a CCNFT for a period of 1 to 10 years (Kumar 2022) and will receive a numerical representation of the carbon sequestration that can be achieved by owning one hectare of forest, similar to an environmental certificate. CCNFTs can motivate the public to protect forests and encourage replanting by compensating forest landowners for the carbon sequestration that occurs in their forests. The concept underlying CCNFTs may be applicable to NFT art. NFT artists might offset art transaction carbon emissions by minting digital artworks with a similar carbon-offsetting scheme. However, CCNFTs use inaccurate forest carbon sequestration values. To be effective, CCNFTs must correctly measure these data.

Another intriguing initiative is MOSS's MCO_2 token, which is an environmental token that combines the concept of carbon credits and blockchain. Moss created the MCO_2 coin in March 2020, the first blockchain-supported global green digital asset (Earth 2022). Companies and individuals can offset carbon emissions by buying MCO_2 digital certificates (MCO_2 n.d.). MOSS bought Amazon jungle land, divided it into virtual currency shares, and distributed them to investors. A specific number of shares control this land, allowing the corporation to raise funds to buy or develop green spaces to attract investors.

Sven Eberwein is a pioneer in NFTs, combining art, sustainability, and technology. Collaboratively, Eberwein and Offsetra have crafted a path toward sustainable digital artistry. Eberwein's "M Carbon Dioxide" is particularly illustrative of this synergy, and this work is the first carbon-neutral NFT. Representing 1000 tonnes of CO_2 offset, this artwork visualizes a world bereft of land, adorned with a million black particles, each denoting 1kg of CO_2 (Eberwein 2020). These emissions were retired as Verified Credit Units

(VCUs) on the Verra registry. To elucidate further, the carbon offset by this singular NFT parallels the emissions produced by an average individual from an industrialized nation over four decades, or equivalently, 500 round-trip transatlantic flights between New York City and London (Offsetra 2020; Kentidas 2022). The NFT, priced at 15 ETH, matches the cost that Eberwein bore to purchase the VCUs, rendering the art as a medium to catalyze climate action (Eberwein 2020). With Offsetra's efforts underpinning this endeavor, such ventures amplify the potential of NFTs to intersect environmental conscientiousness with artistic innovation.

In essence, initiatives like CCNFTs and MCO_2, coupled with the contributions of artists like Eberwein, offer a diverse range of possibilities. These innovative approaches to integrating carbon credits and blockchain technology provide individuals and businesses with a unique investment opportunity. This not only satisfies the investors' desire for sustainable and environmentally beneficial investments, but also demonstrates their dedication to combating climate change. The difficulty lies in modifying these strategies effectively and precisely for NFT art, ensuring that they not only contribute to reducing carbon emissions but also preserve the integrity and appeal of the art form.

3.1.3. Limitations of Carbon Neutrality

As explored in Sections 3.1.1 and 3.1.2, the concept of carbon neutrality has been embraced by many in the NFT art world as a step toward sustainability. Nevertheless, while carbon-neutral NFT art projects signify a paradigm shift in addressing environmental repercussions, there remain pertinent limitations to be addressed:

First, the current data used to calculate carbon offsets is inaccurate, and multiple agencies lack mutual oversight. Nifty Gateway wants to become "carbon negative" by buying twice its CO_2 emissions in carbon offsets. Nevertheless, the intricacies surrounding the methodology employed to ascertain its carbon footprint raise significant questions. The platform uses Kyle McDonald's open-source calculator to account for data discrepancies that could double or halve its emissions (Di Liscia 2021). These ambiguities highlight the limitations of carbon offsetting in NFTs and the need for thorough data analysis.

Secondly, it does not result in a significant reduction in carbon emissions because it does not fundamentally change the carbon-related behaviors of individuals. This is because the crux of the problem lies not just in offsetting emissions but in the overall behavioral patterns associated with carbon production. Art Basel Miami Beach illustrates the limits of carbon offsetting in the art sector. The fair organizers vowed to reduce their carbon footprint (Rea 2019). This does not necessarily reduce carbon emissions. Critics argue that emissions should be totally eliminated rather than maintained at existing levels. (Rea 2019). This issue applies to NFT art, where carbon neutrality may encourage careless trading without meaningful carbon emission reduction efforts. Notably, carbon offsetting is not a panacea; tackling carbon-producing habits is.

Lastly, there is no guarantee that initiatives to reduce carbon emissions will be effective in the long term. Offsetting carbon emissions may take time, or the carbon conserved may be released back into the atmosphere, negating any long-term advantages. The famous band Coldplay has long been carbon neutral. The band promised various eco-friendly steps for its 2022 global tour, including lowering CO_2 emissions by 50% and using renewable energy. Innovative methods included a "kinetic floor" to harness fan energy, planting a tree for each ticket sold and solar panels at venues (Beaumont-Thomas 2021). Although commendable, these approaches emphasize that this is a long-term commitment that will take years to pay off. While commendable, these efforts do not guarantee that the carbon avoided now will not be released into the climate in the future. Therefore, we must keep seeking better, more sustainable alternatives.

To overcome these constraints, carbon-offset requirements need tougher and more independent audit methods, such as third-party verification and continuous program audits. Recognized carbon standards like the Verified Carbon Standard (*Verified Carbon Standard Methodologies* n.d.) should be used. While some mechanisms such as third-party

verification and continuous program audits aim to ensure robustness in carbon-offset measurements, the efficacy of such standards is subject to ongoing scrutiny and debate, as evidenced by recent controversies questioning the reliability of dominant standards in the voluntary offsets market. Recent incidents have questioned the Verra carbon standard, which dominates the USD 2 billion voluntary offsets market. The Guardian, Die Zeit, and SourceMaterial found that more than 90% of their rainforest offset certificates are likely "phantom credits", and they do not reduce carbon emissions (Guardian News and Media 2023).

This suggests that well-known worldwide firms, some of whom call their products "carbon neutral", may increase global warming by buying credits. Addressing data inaccuracy requires more stringent and independent audit procedures for carbon-offset standards, such as third-party verification and continuous audits of carbon-offset efforts.

Carbon-neutral NFT art is an innovative way to address the environmental impact of the NFT art ecosystem, but it is important to acknowledge and address its limits. By improving carbon-offset standards' transparency, precision, and oversight, the NFT art market can gain credibility and promote environmental responsibility. As the sector evolves, solutions must prioritize carbon neutrality and a more comprehensive and sustainable approach to environmental preservation.

3.2. Lazy Minting

Creators can use lazy minting to reduce the environmental impact of NFT art, and as the technology evolves, the platform can push it as its primary minting method. After an asset is created and documented in a smart contract for trading, minting adds data to the blockchain's main network (Chandra 2022). The carbon footprint of this process includes computing, storage, and transaction costs. It is pertinent to note that unsold NFT artworks, once minted, continue to occupy valuable storage capacity in the blockchain and contribute to environmental degradation through the energy utilized in their minting process.

Lazy minting involves the buyer paying the minting charge after the sale (Alchemy 2022). By avoiding the minting and energy use of unsold NFT artworks, this technique reduces creator costs and increases environmental sustainability. This architecture requires the seller to presign a smart contract with a wallet, token ID, and pricing information. The NFT is minted and transferred to the buyer's wallet to complete the transaction (NFT School 2021). Lazy minting reduces unsold NFTs, making it more eco-friendly.

Platforms renowned in the NFT art realm, like OpenSea and Rarible, have utilized lazy minting as an option (Atallah 2022; Rarible 2021). Lazy minting allows developers to generate NFTs for free, but it is currently only an optional method that many creators may not choose. Lazy-minting technology has the disadvantage that sellers potentially lose control over their work and there is the risk of fraud (Phemex 2022). The smart contract may mint NFT art immediately once it is sold and sent to the buyer, ensuring that the author receives a part of future sales. This would keep using the more ecologically friendly lazy minting process while giving creators some control over their products. Blockchain technology can manage and monitor NFT ownership and transfers, reducing fraud and ensuring that authors have a record of all interactions with their works.

Lazy minting is a more eco-friendly way to make NFT art, despite its challenges. As this technology evolves, new protocols and systems will improve its efficacy and security, making the NFT art market more resilient.

3.3. Alternatives Using Eco-Friendly Blockchain Systems

3.3.1. Alternative Solutions on the Blockchain Main Chain

In response to NFT carbon emissions issues, methods like Proof of Authority (PoA), Proof of Spacetime, and Proof of Good have emerged. Some of these methods have been implemented and produced results, while others are still being conceptualized. NFT art buyers can trade on these platforms, which is pushing them to be more environmentally responsible.

Proof of Authority (PoA)

Back in 2019, the Congressional Research Service recommended PoS and Proof of Authority (PoA) as more sustainable alternatives to PoW for consensus mechanisms (Clark and Greenley 2019). PoA is a consensus mechanism that relies on a set of pre-selected nodes or validators to validate transactions and to create new blocks in a blockchain network (Shardeum Content Team 2022). The PoA system, like that of the PoS, has validators that aid in network agreement. However, in PoA, validators stake their reputation. To enter the chain as a validator, a master of ceremonies must possess a valid United States notary public license and be able to add additional verifiers through the dapp's[2] built-in voting procedure governance (POA n.d.). The PoA system establishes trust and ensures consensus via a combination of identity verification tests and validation by participants who have already been verified.

Due to the performance gains from fewer message exchanges, PoA, a consensus algorithm for permissioned blockchains, has grown in favor (De Angelis et al. 2018). It re-quires less computing power, fewer nodes, and no communication between nodes in order to achieve consensus. Existing nodes are trusted and publicly verified, so the network can still operate with fewer nodes (Curran 2018). In addition, the PoA system has quicker block times and a significantly higher transaction throughput than the PoS system (Majer 2022), uses less energy, and emits less carbon dioxide.

However, the PoA consensus algorithm may limit decentralization and scalability. PoA risks centralization if a few validators conspire or are compromised, since they depend on a collection of validators. The fixed number of validators may also slow transaction processing as the network grows. A potential blockchain network carbon emission substitute is PoA's effective consensus technique, despite its scalability and decentralization limitations. To encourage more NFT artwork transactions based on PoA platforms (such as xDai and POA networks), interoperability must be guaranteed between existing NFT platforms and PoA-based platforms to preserve NFTs' distinctive qualities and value.

Proof of Spacetime (PoST)

The Chia blockchain platform created Proof of Spacetime (PoST), a distributed ledger technology agreement technique based on timestamping data segments to solve energy industry issues while ensuring network security (Chia 2023). PoST might considerably lower NFT art platforms' carbon impact.

PoST validators must stake cryptocurrency to participate in a consensus. They are more likely to be validators and receive incentives if they keep their stake. Because this method encourages validators to keep their coins longer, trading is less frequent, transaction fees are lower, and energy-intensive mining is less necessary. PoST employs hard drives and storage instead of power-hungry, single-use computing hardware that does not need validators' processing power. The Chia network utilizes 0.3% of Bitcoin's annual energy consumption, compared with PoW (*Intro | Chiapower* 2023; Digiconomist 2023). PoST's reduction in energy consumption could lead to a significant decrease in the carbon emissions associated with the minting and trading of NFT artworks. This makes it a more sustainable alternative to traditional, energy-intensive methods.

PoST reduces environmental impact; however, hard drive energy usage is crucial. PoST may increase hard drive usage and electronic waste. After forty days of Chia mining, a 512GB SSD's storage capacity would be gone, according to Fast Technology (Xian 2021).

In conclusion, PoST-based NFT platforms can reduce carbon emissions by utilizing a more energy-efficient consensus mechanism, thereby reducing the total energy consumption associated with the NFT artwork traded on this platform. Notably, the effects of energy supply and the increasing demand for hard disk devices must also be addressed.

3.3.2. Layer 2 Protocols

As an alternative to the mechanisms described above that operate on the main chain, additional mechanisms can be used to reduce NFT art emissions and preserve the decentralized nature of the network (Calma 2021). Adding another "layer" to the current blockchain, which already operates in tandem with Ethereum, is one possible solution. Layer 2 protocols add scalability frameworks to Layer 1 blockchains like Bitcoin and Ethereum. These additional mechanisms, such as sidechains and rollups, aim to lower NFT emissions while preserving the network's decentralized nature (Ginsburg 2022).

Rollups aggregate numerous transactions into one before submitting it to Ethereum for verification, minimizing computing overhead and energy use. NFT art creation and transactions are more carbon-friendly. Arbitrum and Optimism, two popular Ethereum rollup solutions, have 95% lower swap fees than Ethereum's base network (*L2fees.info* 2023). NFT artists and collectors can mint and trade NFTs on Immutable X and Polygon using Layer 2 solutions. These platforms allow NFTs to be transferred to Layer 2-based networks, saving energy.

Layer 2 presents a number of challenges in addition to its many strengths. Layer 2 networks confine interactions to a protocol (RAILGUN Project 2021), limiting communication with Layer 1 (Adede 2023). For instance, rollups may limit Ethereum's compatibility. This may fracture the NFT art ecosystem, forcing developers and traders to adapt to many marketplaces and platforms, which may slow asset transfers between networks, complicate monitoring, and increase complexity (Murphy 2022). End users may also find Layer 2 solutions more complicated as they learn new platforms and technologies. This learning curve may deter users and result in slow adoption.

Despite these challenges, Layer 2 scaling solutions like rollups may reduce NFT art's carbon footprint without affecting efficacy or security as the blockchain industry grows. Therefore, opting for Layer 2 platforms may be a beneficial choice for reducing one's carbon footprint. They need continuous study and development to provide a more sustainable and user-friendly environment for NFT art creation and exchange.

3.4. Calculating the Carbon Emissions of NFT Art

Numerous businesses and individuals, including Digiconomist, NonFungible, DappRadar, and Kyle McDonald, actively track daily NFT transactions and carbon emissions on the blockchain. Their data can be extrapolated to inform and influence the NFT art sector in particular. This real-time monitoring and reporting serve as a valuable tools for those in the NFT art community to comprehend the environmental implications of their actions.

In addition, specialized groups like the Crypto Carbon Ratings Institute (CCRI) have developed methods to determine the carbon emissions of particular NFT transactions for consumers (CCRI-Crypto Carbon Ratings Institute 2022). This encourages more sustainable investments in the NFT art market by enabling consumers to make informed choices about the environmental impact of their purchases. While applicable to the entire continuum of NFTs, the CCRI's approach can be utilized to comprehend the environmental impact of NFT art transactions, thereby empowering consumers to make more sustainable decisions.

Joanie Lemercier, a French climate activist artist, illustrates this need for transparency. Despite his efforts to reduce his carbon impact, NFT art presented unforeseen problems. After successfully selling his artwork as NFTs, he wanted to evaluate his carbon footprint. To his disappointment, Lemercier had trouble obtaining accurate and transparent data from his sales on Nifty Gateway. Joanie Lemercier consulted Offsetra, a carbon-offsetting expert, to analyze the environmental impact of his digital artworks. He learned that his NFTs equated to 80 kg of CO_2, undermining many of his carbon footprint reduction efforts (Mattei 2021). These occurrences demonstrate the importance of open and clear communication about NFT art's potential carbon emissions.

Another NFT community, NFT Club, offers a convenient tool to help NFT creators and collectors become more aware of their environmental effect by allowing users to calculate their carbon footprint by entering the quantity of NFTs issued and traded (NFT

Club n.d.). The Gallery Climate Coalition (GCC) concentrates on the physical art world by monitoring carbon emissions from art shipments (Gallery Climate Coalition 2023). This effort is crucial for highlighting the need for sustainable practices in the traditional art market and for increasing awareness of carbon reduction among art trading parties, galleries, and institutions.

The monitoring and calculation of carbon emissions are essential for effectively addressing and reducing the environmental impact of NFT art. By utilizing these tools, the NFT art community will be able to resolve environmental concerns in a more proactive manner, potentially resulting in a shift toward NFT artworks with smaller carbon footprints. As a result, this rising awareness, in turn, will foster the adoption of environmentally friendly blockchain systems and procedures in the NFT art industry.

3.5. Policy Interventions

Post the Merge in September 2022, Ethereum transitioned from a PoW to a PoS mechanism, significantly diminishing its energy consumption and consequential environmental impact. The reverberations of this transition were felt across various domains, including the NFT art sector. The NFT art market, intrinsically linked with blockchain technology, is directly influenced by such transitions in the digital currency space. It is essential to comprehend and anticipate how policy adjustments affecting the broader blockchain ecosystem may inadvertently affect the NFT art market.

Before the Merge, a plethora of policy propositions were in the limelight to instigate a deviation from the energy-intensive PoW mechanism. These included endorsing alternative consensus mechanisms and proposing regulations that mandate environmental assessments for PoW. Additional fiscal measures, such as fluctuating transaction sales taxes or energy-driven income tax rates, were put forth to stimulate the adoption of eco-friendly consensus processes.

These measures, while not tailor-made for NFT art, hold significant referential significance as they showcase how fiscal incentives and disincentives can shape industry behavior toward sustainability. In essence, by analyzing these policies and understanding their impact on related sectors, stakeholders in the NFT art space can glean valuable insights and be better prepared for potential shifts in the regulatory environment, ensuring the sustainable growth of the sector.

3.5.1. Regulations Prohibiting the Trading or Mining of Virtual Currencies

Various jurisdictions have adopted diverse industry-focused policy interventions in an effort to reduce the carbon emissions associated with blockchain activities, including the creation and trading of NFT art. As seen in China, the United States, and Iran, one such strategy is the implementation of prohibitive regulations on miners and financial institutions. Since 2018, the number of countries with cryptocurrency bans has increased substantially. In 2018, there were eight jurisdictions with absolute bans and fifteen with implicit bans.[3] By November 2021, the number of jurisdictions with absolute bans increased to 9 and the number of jurisdictions with implicit bans increased to 42 (Regulation of Cryptocurrency Around the World: November 2021 Update 2021).

China is an example of a country that has restricted not only mining operations but also the ability of financial institutions to conduct digital currency transactions. China enacted a rule in May 2021 that prohibited a variety of activities involving virtual currencies. This rule bans the use of cryptocurrencies like Bitcoin, Ethereum, and Tether as legal tender, exchange services, information intermediaries, token issuance, and derivative trading. The policy also penalizes people and organizations for virtual currency activity (*Notice on Further Preventing and Resolving the Risks of Virtual Currency Trading and Speculation Act* 2021). This also has significant implications for the NFT art industry, as it restricts transactions and exchanges involving NFT art.

According to the Cambridge University data, Bitcoin mining's carbon footprint has decreased substantially as a result of China's crypto crackdown, which forced more than half of the global hash rate[4] offline, as shown in Figure 3. This implies less operational mining hardware and reduced energy consumption, which indirectly impacts the environmental footprint of NFT art creation and trading, given that Ethereum and Bitcoin employ comparable consensus mechanisms.

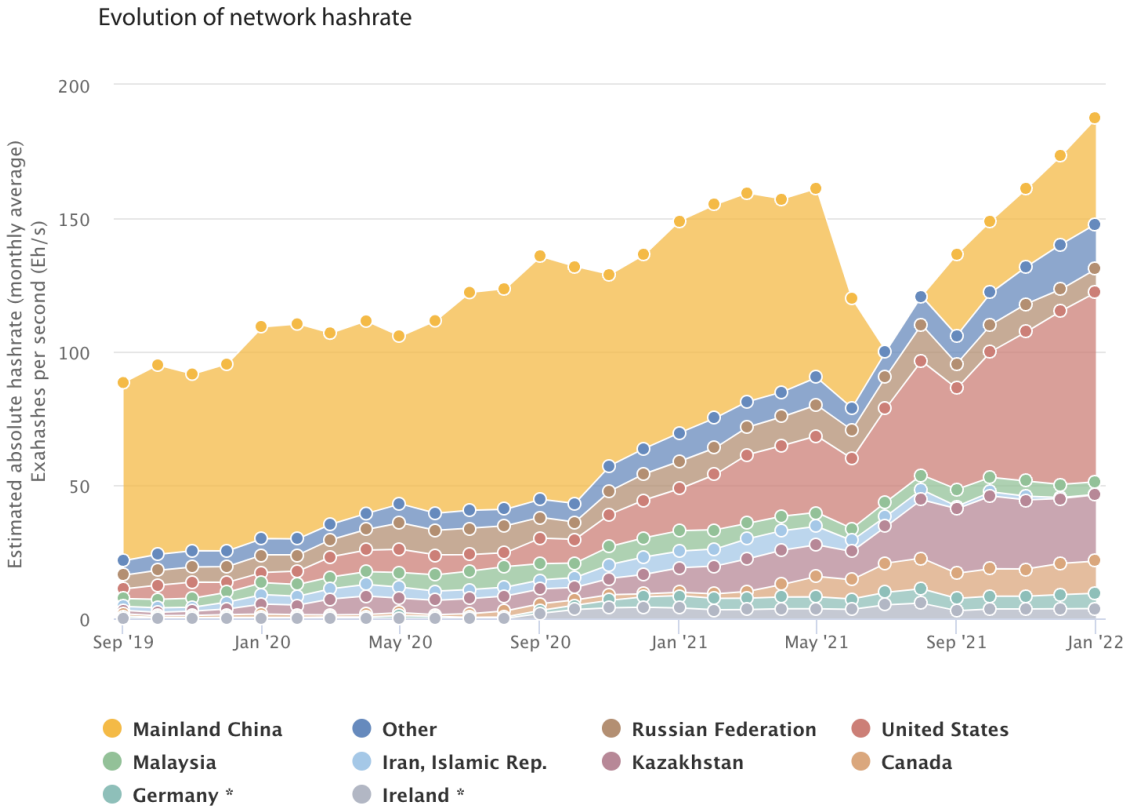

Figure 3. Evolution of the global Bitcoin network hashrate map as of January 2022. * ***Note.*** The data is from (Cambridge Centre for Alternative Finance n.d.) *Bitcoin Hash Rate*. The Cambridge Bitcoin Electricity Consumption Index (CBECI). Retrieved 18 March 2023, from https://www.blockchain.com/charts/hash-rate. Copyright 2023 by Cambridge Centre for Alternative Finance.

Despite the fact that China's policy is a step toward reducing the carbon footprint of NFTs and the blockchain industry, it has distinct limitations that must be acknowledged. Firstly, the policy only restricts mining operations within China's borders, so miners can simply move their operations to countries with reduced electricity costs, such as Kazakhstan, Russia, and Iran, and continue to contribute to high carbon emissions. Numerous Chinese Bitcoin miners have relocated to nations with lower and more renewable energy sources, such as the United States, which is now home to 37.84% of the world's Bitcoin miners (Kavanagh 2022). Secondly, while the policy encourages the use of renewable energy, it does not inherently require it, so mints may continue to rely on fossil fuels to power their operations. Thirdly, the policy focuses primarily on reducing carbon emissions from mining while ignoring other aspects of NFT art creation and trading and the blockchain industry that contribute to environmental degradation, such as the energy consumption required for transactions and storage. Fourthly, there may be difficulties in enforcing the policy, specifically in identifying and penalizing individuals and organizations that continue to engage in NFT art-related activities with a high carbon footprint. This could hinder the policy's ability to reduce the environmental impact of NFTs. China's policy is a positive step toward reducing the environmental impact of the NFT art industry, but it is not a

comprehensive solution and must be accompanied by additional efforts to address the limitations and assure the industry's sustainable future.

3.5.2. Imposing Fees for Energy Consumption

An effective policy approach to reducing the carbon footprint of NFT art could involve internalizing the environmental costs associated with energy consumption during the minting process. Internalizing the environmental costs of energy consumption by instituting surcharges or fees on the energy used in the minting process is an effective policy strategy for reducing carbon emissions associated with the production of NFTs (Truby et al. 2022). This approach, inspired by the increased fees imposed on miners in New York, adheres to the "polluter pays" principle, according to which those who profit from energy consumption should cover the costs of environmental damage caused by their energy use (PSC Approves New Cryptocurrency Electricity Rates for Upstate Utility 2018).

Implementing these costs may encourage energy users to reduce their energy consumption or transition to greener, more sustainable energy sources. Furthermore, this policy could be devised to target high-energy consumption activities associated with NFT art minting, such as PoW algorithms, by imposing a tiered fee structure that levies higher rates for more energy-intensive processes. Revenue from these surcharges could also fund clean energy infrastructure or renewable energy projects, accelerating the shift to a low-carbon economy. International cooperation and planning can prevent carbon leakage and tax competition, achieving the policy's environmental aims without compromising the NFT art market's global competitiveness.

3.5.3. Fiscal Measures to Reduce Carbon Emissions from Cryptocurrency and Blockchain Mining

A variety of measures have been proposed to mitigate the environmental impact of blockchain technology and the creation and trading of NFT art in light of escalating environmental concerns. Environmentalists and policymakers are concerned about the rising carbon emissions caused by NFTs and blockchain mining. In response, various tax measures to mitigate the environmental impact of these technologies have been proposed, including carbon tariffs on blockchain mining, tax breaks or incentives for energy-efficient technologies, implementation of a cap-and-trade framework, taxes on electricity consumed by NFT art and blockchain mining operations, and a tax on NFT art transactions that differs based on the carbon footprint of the underlying blockchain technology. These measures are predicated on the evolution of a carbon tax, which substantially reduces the use of fossil fuels and their environmental impact.

A carbon tax is a fee established by the government whereby emitters must pay per tonne of greenhouse gases emitted. (Center for Climate and Energy Solutions 2021) Sweden's carbon tax, for instance, was implemented in 1991 and is one of the world's earliest and most extensive carbon taxes. It taxes fossil resources like coal, oil, and natural gas according to their carbon dioxide emissions (*Sweden's Carbon Tax* n.d.). The tax has been instrumental in reducing greenhouse gas emissions in Sweden and advocating the use of clean energy. Following is a discussion of several tax policy strategies that could reduce the carbon emissions of NFT art.

Carbon Tariffs on Blockchain Mining

Envisage an art gallery powered predominantly by non-renewable energy; the carbon tariffs on blockchain mining would motivate NFT art creators to pivot toward greener alternatives. By instituting a tax on energy usage and carbon emissions resulting from various consensus protocols, policymakers have the potential to incentivize miners to adopt greener energy sources and to invest in energy-efficient technology. The tax structure could be designed with a gradient approach, in which less efficient equipment would be subject to higher taxes and more efficient equipment with diminished environmental impacts would be subject to lower taxes.

Tax Breaks or Incentives for Energy-Efficient Technologies

Art has always been an avenue for innovation, and with fiscal incentives, NFT artists and platforms could be at the forefront of technological advancements. Governments could provide tax breaks or incentives to NFT artists and platforms who invest in energy-efficient technologies or use renewable energy sources. This policy could stimulate industry innovation and increase the demand for green technologies by providing financial support for environmentally favorable practices in the NFT art sector. For instance, federal tax credits for solar energy systems in the United States illustrate the potential influence of such incentives on industry behavior (*Homeowner's Guide to the Federal Tax Credit for Solar Photovoltaics* 2023). The federal tax credits are an excellent example of how incentives can influence industry behavior.

Cap-and-Trade Framework

The implementation of a cap-and-trade framework is an alternative method for reducing carbon emissions in the NFT art sector and other blockchain mining industries. This market-based mechanism establishes a cap on total allowable emissions while distributing or auctioning permits to mining companies. NFT art creators are then incentivized to reduce their emissions in order to trade excess permits or avoid the need to obtain additional ones. The European Union Emissions Trading System (EU ETS) is an example of a successful cap-and-trade program that has effectively reduced emissions across multiple sectors; installations subject to the ETS have experienced a reduction in emissions of approximately 35% between 2005 and 2021 (European Comission Climate Action 2023). By employing a similar cap-and-trade system, the NFT art industry could potentially achieve comparable environmental mitigation results.

Taxes on Electricity Consumption

In addition to the aforementioned strategies, a tax on the electricity consumed by NFT art could encourage the adoption of energy-efficient equipment and practices. Governments can indirectly target carbon emissions associated with energy consumption through the imposition of taxes on energy consumption. The Climate Change Levy (CCL) of the United Kingdom, which taxes the energy consumption of enterprises, is one policy that promotes energy efficiency and the use of renewable energy sources (*What Is the Climate Change Levy (CCL)?* n.d.). By imposing taxes on electricity consumption, much like the UK's Climate Change Levy, NFT artists would be nudged toward more energy-efficient modes of creation and exhibition.

NFT Art Transaction Taxes Based on Carbon Footprint

Lastly, a tax on NFT art transactions that varies based on the carbon footprint of the underlying blockchain technology could encourage users to adopt platforms with minimal emissions. There is a need for tax regulations that fluctuate based on the carbon footprint of the blockchain technology underlying NFT art transactions. Currently, while certain NFT transactions, such as purchasing an NFT with fiat currency, are not taxable, the taxation rate can vary significantly depending on whether you are an investor or a creator (Brooks 2023). To effectively combat the environmental impact of NFT transactions, fiscal measures that incentivize users to gravitate toward platforms with minimal emissions should be implemented. Not only would such a policy internalize environmental costs, but it would also ensure that the art market remains acutely aware of the environmental consequences of its choices (Coinbase n.d.).

A combination of tax policy strategies could effectively reduce carbon emissions related to NFT art. By encouraging the adoption of cleaner energy sources, energy-efficient technologies, and more sustainable practices within the industry, these measures have the potential to significantly mitigate the environmental impact of this swiftly expanding sector. In essence, by integrating these tax policy strategies into the NFT art realm, there is an

avenue to sculpt a future where art not only reflects our culture but also our commitment to the planet.

4. Conclusions

In recent years, the NFT art market has witnessed remarkable growth, with transactions totaling billions of dollars. NFT art that operated primarily on Ethereum and utilized the PoW mechanism was energy-intensive and generated significant carbon emissions. The adoption of a PoS system by Ethereum reduces carbon emissions. Despite the fact that this is a positive development, the underlying blockchain technology incurs energy costs for sustaining multiple instances, which must be addressed.

This paper compares and analyzes the options proposed by experts and the NFT art platforms prior to the Merge to determine the carbon reduction strategies that are still useful. Carbon neutrality is a possible remedy. CCNFTs and MCO_2 offset the carbon footprint of NFTs with carbon credits. However, their high cost and the imprecision of carbon-offset data calculations limit their efficiency. Although lazy minting is a viable solution, it results in creators losing control over their own works. Alternative solutions on the blockchain, including PoST and PoA on the mainnet and Layer 2 systems, have been implemented. Notwithstanding, new issues have emerged, including, among others, decreased dispersion, increased demand for hard drives, decreased connectivity, and emerging information security concerns. There is no single solution that combines the advantages of all stakeholders; all existing alternatives have glaring disadvantages. These methods, despite their limitations, can significantly reduce the carbon footprint of NFT art.

Numerous policy interventions have been discussed, including regulations prohibiting the trading or mining of virtual currencies, the imposition of fees for energy consumption, and fiscal measures to reduce carbon emissions from cryptocurrency and blockchain mining. While Ethereum's successful transition to a PoS system has deemed many of these policy interventions irrelevant to the Ethereum network, they may still be applicable to other blockchain platforms utilizing PoW consensus methods. These interventions could promote the industry's adoption of healthier energy sources, energy-efficient technologies, and more sustainable practices.

In conclusion, sustainability and environmental impact mitigation must be prioritized as the NFT art market expands. Combining tax policy strategies, such as carbon taxes on NFT art minting, energy efficiency tax credits, tradable emissions permits, energy consumption taxes, and NFT art transaction taxes, with technical solutions such as carbon offsets, lazy minting, and alternative consensus mechanisms can assist in addressing the environmental challenges posed by NFT art. These measures have the potential to substantially mitigate the environmental impact of this rapidly expanding sector by encouraging the adoption of cleaner energy sources, energy-efficient technologies, and more sustainable practices within the industry.

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1. Ethereum Energy Consumption: The quantifiable metrics pertinent to Ethereum's energy utilization, inclusive of those associated with Ethereum's Proof of Stake (PoS) mechanism, were acquired from Digiconomist's (2023) Ethereum Energy Consumption Index. This repository is accessible to the general public and can be retrieved from the following URL: https://digiconomist.net/ethereum-energy-consumption/. The dataset is copyrighted by Digiconomist, thereby requiring acknowledgment for its reproduction or dissemination.
2. Ethereum PoS Mechanism: Data delineating the energy implications of Ethereum's Proof of Stake (PoS) mechanism have also been sourced from Digiconomist's "Ethereum Energy Consumption Index," accessible as of 1 February 2023. This is the same database as the aforementioned Ethereum energy consumption data, and it is copyrighted by Digiconomist.

This repository is accessible to the general public and can be retrieved from the following URL: https://digiconomist.net/ethereum-energy-consumption/.

3. Mastercard Energy Consumption: The analytical data germane to Mastercard's energy consumption has been culled from a copyrighted 2019 sustainability report released by MasterCard USA. Due to intellectual property rights, direct sharing of this dataset is inhibited. However, interested scholars can procure the data from the following URL: https://www.mastercard.us/content/dam/mccom/global/aboutus/Sustainability/mastercard-sustainability-report-2017.pdf.
4. Bitcoin Hash Rate: For assessments related to Bitcoin's energy consumption, data was procured from the Cambridge Centre for Alternative Finance's Bitcoin Electricity Consumption Index (CBECI). This dataset is also publicly accessible and can be found at the following URL: Cambridge Bitcoin Electricity Consumption Index (CBECI). Copyright permissions apply as dictated by the Cambridge Centre for Alternative Finance.

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Notes

[1] The method of capturing and storing carbon dioxide in the atmosphere is called carbon sequestration (Clear Center 2019).

[2] A decentralized application (dapp) is an application that combines a smart contract and a frontend user interface and is created on a decentralized network. Source from *Introduction to dapps* (Introduction to Dapps. ethereum.org n.d.).

[3] In the report of the (Regulation of Cryptocurrency Around the World: November 2021 Update 2021), the term "absolute ban" is defined as a country that prohibits the use or operation of cryptocurrencies through legislation or official statements issued by government or financial regulators. Clearly, cryptocurrencies are prohibited under this prohibition.The term "implicit ban" refers to restrictions that make it difficult or impossible to use or operate cryptocurrencies in a country without explicitly prohibiting them. Bans on banks, banking entities, and cryptocurrency exchanges are implicit bans. These steps restrict cryptocurrency use and adoption in the jurisdiction without outlawing them.

[4] Hash rate is a measure of a cryptocurrency network's computing power that functions as a key security indicator. It indicates the number of approximations made per second to solve complex mathematical puzzles using transaction data. A high hash rate indicates that many processors are validating transactions (Kavanagh 2022).

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