THE LINUX FOUNDATION | Research

The Carbon Footprint of NFTs:

Not All Blockchains Are Created Equal

April 2022

By Alan Majer, *Good Robot*

With a foreword by Daniela Barbosa,
Executive Director, *Hyperledger Foundation*

In partnership with:

HYPERLEDGER FOUNDATION

Palm NFT Studio

Contents

Foreword

As the executive director of Hyperledger Foundation, I believe that 2022 will be not only a year of growth and acceleration for our enterprise blockchain ecosystem but also a shift toward a more robust dialogue about the climate impact of blockchain, particularly for non-fungible tokens (NFTs). NFTs have gone from not even registering on Gartner's "Hype Cycle for Emerging Technologies" in 2020 to reaching its "peak of inflated expectations" in 2021. While NFTs have perhaps entered the next stage—the "trough of disillusionment" regarding energy and climate implications—they have rapidly expanded beyond the realm of digital art and crypto asset collectors to broader use cases, including those specific to climate solutions.

To enter Gartner's "slope of enlightenment" and "plateau of productivity," the blockchain and extended community must have a more robust dialogue on the climate implications—beyond the complex measurement of the energy consumption and related climate impact of underlying consensus mechanisms. This report provides key talking points for that dialogue—one that ranges from recognizing the significant efforts of the blockchain community, from the long anticipated transitions to more energy efficient mechanisms by key actors to their central role in laying the foundations for a growing international ecosystem of climate solutions and contributing to the all-important health of the planet.

Since 2016, the Hyperledger ecosystem has been a place for experimentation and innovation. We have worked closely with key stakeholders globally on multiple consensus mechanisms, including defining solutions and use cases within the Ethereum ecosystem. We understand the complexity of Ethereum's long planned and highly anticipated transition to proof of stake (PoS), which promises to reduce the energy consumption of Ethereum by 99.95 percent.[1] We also appreciate that Ethereum supports thousands of layer 2 solutions, which help reduce transactional energy consumption.

Moreover, we recognize that Ethereum and other proof-of-work (PoW) based platforms currently underpin key climate technology solutions ranging from renewable energy to integrated carbon markets, bolstered by the underlying attributes of accessibility, security, transparency, accountability, and traceability. Blockchain is enabling a global network of integrated technology solutions that are expanding to help achieve the goals of the Paris Agreement. NFTs are playing a new role not only in transforming finance models for climate solutions but in engaging new actors across sectors and social strata in climate action.

NFTs are an invention unique in human history. Their role is fast extending beyond the speculative trends around collectibles to use cases that have positive impact. A broad range of physical and virtual assets can be authenticated providing transparency on ownership and underlying attributes of the assets tokenized while preserving privacy of individual owners. In fact, IBM and IPwe are collaborating on using NFTs to represent intellectual property (IP), bringing greater transparency as well as increased accessibility and efficiencies—in both time and costs—to the process.[2] Together, these benefits make patents easier to sell, trade, or monetize. Artists and musicians can embed royalty shares, celebrities can leverage NFT platforms offering direct donations to charities, conservation organizations can represent individual endangered species for fundraising and transparency about impact, brands can leverage NFTs in authenticating real and virtual goods, and suppliers can provide supply chain traceability.

NFTs afford collaborators, consumers, and donors transparency and accountability while making related transactions simpler and more cost efficient. The expanding innovation models surrounding NFTs are also paving the way for us to embed verified energy and climate disclosures in transactions. As such, NFTs are central to new business models—and new economies—that span social and geographic barriers and provide a means of engaging diverse actors in new experiences and innovative approaches with impact.

This report lays out key climate-related barriers to NFTs and suggests some concrete strategies for embracing and building on the exciting innovations that NFTs enable. Adopting these strategies may unlock new opportunities for global collaborations and partnerships for impact through responsible and potentially beneficial approaches to climate solutions. We hope it will help organizations consider what really matters beyond the hype and undertake their innovative initiatives in a climate-friendly way.

Daniela Barbosa
Executive Director
Hyperledger Foundation

Abstract

NFTs are a class of assets underpinning the worlds of digital art, digital collectibles, metaverse gaming, and beyond, that have exploded in popularity. At the same time, they have been met with skepticism, tainted by market hype, and associated with energy-intensive PoW consensus mechanisms. For proponents of NFTs, this is just the beginning. They represent an opportunity for innovation across a number of different industries. However, not all NFTs are equal. Linux Foundation Research, in collaboration with Hyperledger Foundation and Palm NFT Studio, has conducted a new research project to explore the environmental impact of NFTs, including those using Hyperledger Besu, investigating how and why NFTs can have varying carbon footprints depending on underlying technology stacks. This study uses qualitative methodologies to capture insights from carbon market experts, blockchain innovators, and open source community leaders. It describes the process by which innovators can choose sustainability by design. Finally, this research draws upon reviewed papers that have calculated and compared levels of energy use and impact.

Introduction to the Environmental Concerns Around NFTs

The NFT is a new digital asset class that has soared in popularity. In 2021 the value of transactions for digital collectibles and other forms of NFTs hit $44.2 billion.[3] Generative media NFTs (often using unique variations based on algorithms) have proven extremely popular, and the value of collections such as CryptoPunks and Bored Ape Yacht Club have soared. (See **FIGURE 1** for an example of media generated by artificial intelligence). Yet, where some see a beacon of rapid innovation, others see a frothy speculative bubble. (See the sidebar, "The NFT Backlash.")

This report does not dwell on the NFT backlash or the potential hazards of speculation. Instead, this report examines a very serious and real challenge: the link between NFTs and climate impact. We look at the problematic energy use for specific types of blockchains as well as several emerging blockchain technologies that can reduce or eliminate these harms. Becoming aware of these challenges is the first step to making informed choices. Only then can we leverage all the benefits of NFTs while navigating those choices to lower climate impact. Everyone must become aware of the existing alternatives and shift behavior toward environmentally sound practices.

FIGURE 1

Crypto Steampunk Pups **generated by artificial intelligence**

The NFT Backlash

Rapid growth in NFTs has fueled what many are terming a speculative bubble.[4] Expectations are running high. The need for enterprises to innovate, as well as fear of missing out (FOMO), drives investments in both promising and dubious initiatives alike. This fuels rapid NFT innovation in some areas, but inevitably, disappointment in others. Gartner, a technology research firm, has documented similar cycles in many different industries. The firm has developed a technology adoption cycle to describe it. In its most recent report, Gartner deemed NFTs to be in the part of the cycle it calls the "peak of inflated expectations."[5] This peak is typically followed by a "trough of disillusionment" (later followed by a "slope of enlightenment" and "plateau of productivity"). This may be an apt description of where NFTs stand today: there's a lot of excitement, but the industry is still figuring things out.

Amid this meteoric rise of NFTs is growing dissent, articulated by those like Dan Olson in videos like "Line Goes Up: The Problem with NFTs." Even those who disagree with its conclusions are likely to find it a thoughtful and well-researched piece. In addition, scams such as "rug pulls," "wash trades," and money laundering have cast a shadow over NFTs. Serious collectors and fans are being priced-out of the things they love by speculators. Perhaps most relevant of all, NFTs are villainized as environmental travesties, fueled by nightmarish proportions of energy that are destroying the planet.

These criticisms are enough to dampen the enthusiasm of even the most ardent supporters. Yet the same echo chambers and zealotry that drive speculative bubbles can also work in reverse. Some will see photos of apes worth millions and then dismiss an entire category of innovation because of it. Zealotry of any kind is unhelpful. Rational approaches are not caught up in either the irrational hype nor the disillusionment that often follows. Put simply, we seek to identify the unique set of affordances that NFTs offer and apply them to the use cases in which they're most needed. That way, we don't diminish the platforms and use cases that can have a positive impact.

Backlash over NFTs risks throwing the baby out with the bathwater. Certainly, there are urgent issues. Speculation certainly exists and sometimes alienates true collectors. Yes, PoW blockchains use a devastating amount of electricity—that's the primary issue investigated in this report—but none of this alters the fact that NFTs are inventions unique in all human history. On a technical level, NFTs offer novel opportunities for a broad range of assets and authentication mechanisms. Sure, we've had bearer bonds, titles, and certificates, but they've all been vulnerable to fraud.[6] Implemented correctly, NFTs change that dynamic completely by addressing issues of forgery, double counting, providence, and authenticity. On a practical level, these capabilities create unprecedented opportunities for engagement and community building. The interest in (and even the hype around) NFTs is what fuels innovation, said Daniel Heyman, co-founder and CEO, Palm NFT Studio: "If NFTs weren't having this moment, we wouldn't get the mindshare, the engineering talent, the financial capital to build all the building blocks to really transform the way we interact with these assets."[7] NFTs are not merely art objects and collectibles, though they can be. So, while popularity is driven by this early use case, ultimately, this may fade in importance relative to other exciting new opportunities, which today remain largely untapped.

Certainly, there are urgent issues. Speculation certainly exists and sometimes alienates true collectors. … but none of this alters the fact that NFTs are inventions unique in all human history.

The Use Case Examples of NFTs

While healthy skepticism and backlash to hype is inevitable, the use cases for NFTs on the blockchain are immense. From major entertainment franchises to sports teams, organizations have started to use NFTs to create greater community and engagement with fans. NFTs act as a combination collectible and membership with access to future utility and events for holders. The surrounding community that is created with NFT holders provides an overall richer experience to being part of a fandom. Palm NFT Studio CEO, Dan Heyman, suggests brands and IP owners can, "reimagine the digital relationship between creator and fan—from a rental one with streaming and social media—to an ownership based one, where fans can have a piece of what they love and they can show it off to their friends, which can speak to who they are, and form a part of their identity."[8]

Within the ESG space, companies are looking to bring carbon credits on the blockchain to verify the authenticity of the credits and reduce the risk of double spending by projects. Bringing credits on the blockchain allows for easier audits and trust of conservation projects and their credibility. Additionally, other NFT use cases include real estate titles. Non-fungible tokens that represent physical properties could create a dramatic shift in commercial real estate. Transference of property ownership could be simplified from weeks of lengthy paperwork process down to minutes, streamlined securely on the blockchain. The potential for NFTs in the future is only increasing as more people are looking to disrupt ineffective processes and shift ownership to creators and supporters.

NFTs are going through a phase of innovation not only on the use case level but also for their efficiency and energy usage. With the creation of new consensus mechanisms and increased use of layer 2 networks, later discussed in this report, NFTs are more effective and sustainable and allow more use cases to be possible on the blockchain. This report discusses the various environmental impacts of blockchain technology but also the innovative alternatives that are being designed and developed to drive towards scale.

What does this mean for other blockchains or cryptocurrencies? What's the implication for NFTs? The answer requires rolling up our sleeves on how blockchains work, with an eye toward understanding not how they function today, but how that will change in the near future.

Not All Blockchains Are Equal

Today, the mining activities associated with cryptocurrencies like bitcoin, (which itself is not directly related to NFTs) are taking a huge toll on the environment. Recent estimates suggested that it's responsible for emitting 114.06 megatons of carbon dioxide per year.[9] That's as much as the entire country of the Czech Republic. This is due to "mining" that secures the blockchain and ensures a trusted set of shared records—via what's called a "proof of work" consensus mechanism. Every 10 minutes on average, powerful computers (usually set up in sprawling data centers) around the globe compete (the "work") to solve a computationally difficult math problem (called a hash). The first node to solve it (the "proof") not only gets to write the latest batch of transactions to Bitcoin's global record but also earns a monetary prize denominated in bitcoin. Good for bitcoin miners, but bad for the environment. The damage gets worse as bitcoin appreciates. By one estimate, a bitcoin price increase of 10 percent would be the equivalent of putting 800,000 additional gasoline-powered cars on the road in perpetuity.[10] PoW mining comes at a high environmental cost. To address this problem, we need to be aware of this cost and its underlying factors.

That's the challenge for the Bitcoin blockchain. What does this mean for other blockchains or cryptocurrencies? What's the implication for NFTs? The answer requires rolling up our sleeves on how

blockchains work, with an eye toward understanding not how they function today, but how that will change in the near future. Let's start with a discussion of cryptocurrency mining, the most environmentally damaging aspect of blockchain and proof of work.

Every decentralized system needs a consensus mechanism. That's especially true of any system where high stakes like money are involved. In its earliest incarnations, the "work" of bitcoin mining had only a minor impact on the environment. Satoshi, the alleged creator of Bitcoin, is said to have mined many early bitcoins using a laptop; and until 2010, all mining was still done on CPUs.[11] But growth in the value of bitcoin increased the competition for its rewards, creating a rapid evolution of mining technologies and the effort put toward it.

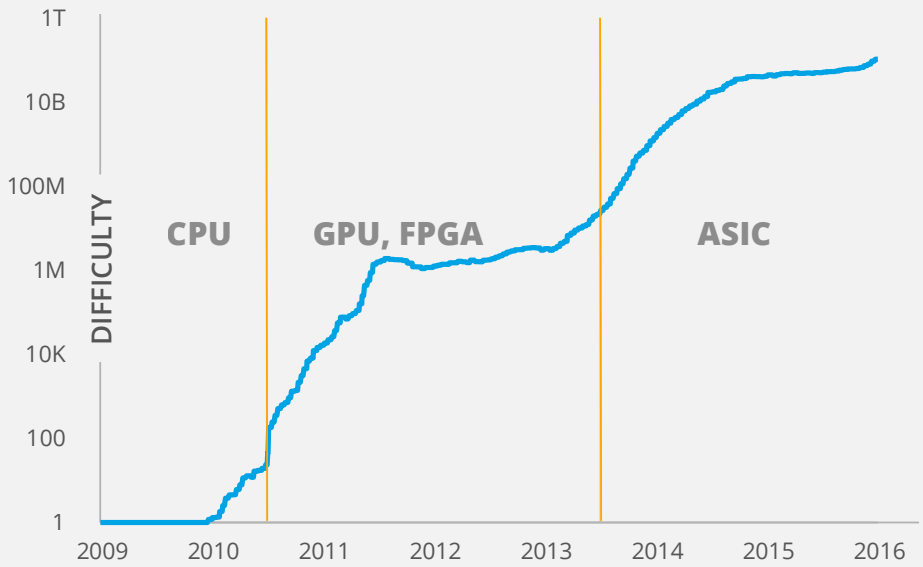
Next came the Ethereum platform (ETH is its native cryptocurrency), which added smart contracts and decentralized applications (Dapps) and used PoW consensus mechanisms. By 2015, the energy consequences of PoW mining at scale were becoming obvious. To address these concerns, Ethereum attempted a new variation of the "work" being done, one that would require more memory-intensive operations and therefore be more resistant to the use of power-hungry ASICs (specialized chips with application-specific integrated circuits) that had taken over bitcoin mining. These tactics have yielded incremental improvements at best and not resulted in a carbon-friendly blockchain (Ethereum's imminent response to environmental concerns is discussed later). Estimates on Ethereum's carbon footprint vary, with some suggesting it contributes as much as 62.69 megatons of carbon dioxide annually.[12] Rising cryptocurrency prices increased rewards available from mining, and the resources devoted to it.

Today, cryptocurrency mining occurs on a massive industrial scale — often involving large data centers filled with specialized high-speed computers — consuming vast quantities of electrical power, with a commensurately large carbon footprint. As of this writing, Bitcoin and Ethereum (the top two blockchains by market

FIGURE 2

Early bitcoin mining difficulty and methods

History of Bitcoin Difficulty by Ladislav, 2016, used under BSD license.



Bitcoin relative mining difficulty chart with logarithmic vertical scale. Higher number means higher difficulty.

CPU: central processing unit
GPU: graphics processing unit
FPGA: field-programmable gate array
ASIC: application-specific integrated circuit

capitalization) both use proof of work as their consensus mechanism. In an effort to significantly reduce total energy consumption, Ethereum has announced it will move to a PoS model in the second quarter of 2022.[13] Together, Bitcoin and Ethereum account for approximately 0.36 percent of human-generated global carbon dioxide emissions.[14]

There's a tremendous push to improve blockchain technologies via other consensus mechanisms that don't require carbon intensive proof of work. An alternate consensus mechanism would:

- Reduce blockchain's carbon footprint
- Protect against coordinated blockchain attacks by increasingly consolidated mining computing power
- Overcome blockchain scaling challenges, which are limited by both slow finality times and low volumes of transactions per second (on Ethereum and many other blockchains)

Proof of stake is an alternative consensus mechanism with a much gentler carbon footprint. Rather than computing to solve computational problems, those in charge of maintaining the blockchain pledge (i.e., "stake") their currency, purposely putting it at risk as a guarantee against fraud. If all goes well, those who stake their tokens can earn a small profit for their trouble. However, if verifiers identify errors or fraudulent transactions, the staked amounts at risk can be slashed or taken. This creates a new kind of consensus mechanism that's based on a balance of trust between parties with strong incentives for honesty and accuracy. Proof of stake is therefore a vast improvement on the purposefully wasteful expenditure of energy on computations that PoW systems require.

So, how far are PoS systems from becoming a reality? The good news is that PoS systems already exist, with the caveat that not all have been proven at scale. Cardano, for example, uses proof of stake and is currently the seventh biggest blockchain with its native token market capitalization of $39 billion.[15] One source suggested that Cardano consumes a total of 2.7 gWh of electricity

So, how far are PoS systems from becoming a reality? The good news is that PoS systems already exist, with the caveat that not all have been proven at scale.

per year, contributing 0.0013 Mt of CO_2.[16] Tezos is another PoS blockchain (ranked 45th by market cap in March 2022), which also claims order-of-magnitude reductions in carbon footprint.[17] However, an even bigger change is set to take place as Ethereum itself migrates from a PoW consensus mechanism to proof of stake, as part of the "Ethereum 2.0" roadmap. This conversion plan has been in the works for years, with upgrades such as the Beacon Chain introducing some staking features in 2020.[18] Full migration to proof of stake is likely to occur in 2022.[19]

Although Ethereum PoS promises order of magnitude improvements in energy consumption, it's not yet available. Those wishing an immediate solution for lower-carbon footprint NFTs have several options available and ready to use:

- ***Layer 2 solutions:*** A layer 2 solution is like a series of lightweight transactions grafted to an existing blockchain. These layer 2 or sharding solutions promise to make Ethereum and other blockchains more scalable with less energy required. They involve a partition that splits off from the main chain (layer 1) and periodically ties back in to assure transaction integrity. A number of layer 2 solutions like Optimism are already operational.
- ***Efficient public blockchain alternatives:*** Public blockchains like Cardano (proof of stake) and Solana (proof of history) have alternative consensus mechanisms and higher transaction throughput that make them attractive candidates for NFTs. Already, these competitors are taking NFT market share from Ethereum.

- ***Sidechains:*** Some of the most energy-efficient blockchain solutions are available through sidechains and private blockchains. Many of these are based on the same technology as Ethereum (e.g., Ethereum Virtual Machine, or EVM), but use alternative consensus mechanisms like proof of authority (PoA), proof of elapsed time (PoET), or others. These sidechains offer some of the most energy-efficient blockchain solutions available, in some cases leaving a footprint that's nearly indistinguishable from other typical Internet transactions.

ConsenSys NFT, part of the Ethereum application and software development organization ConsenSys, actively partners with layer 2 entities to offer sustainable choices. According to ConsenSys NFT's Global Co-Head Johnna Powell:

> *We partner with nearly all major EVM-compatible chains, including Palm, Polygon, Arbitrum, Optimism, NEAR/Aurora, and many more. By doing this, we allow ourselves and our partners to have the flexibility and comfort of 'future proofing' to choose the chain that provides the optimal carbon footprint.*[20]

Proof of Authority (PoA)

Hyperledger Besu implements the QBFT, IBFT 2.0, and Clique proof of authority (PoA) consensus protocols. PoA consensus protocols work when participants know each other and there is a level of trust between them, such as in a permissioned consortium network.

PoA consensus protocols have faster block times and a much greater transaction throughput than proof of work consensus protocols.

How to Reduce Blockchain's Climate Impact

With the high energy consumption and resulting climate impact that most PoW blockchains have, it's natural to ask who should be responsible for addressing solutions.[21] The obvious choice would be cryptocurrency miners, after all, they're typically the ones directly consuming the vast quantities of electricity that mining needs. However, there are a couple of reasons it's not quite that simple.

The Role of Miners

First, miners operate in relative isolation. Alex Taylor, co-founder of Offsetra, said, "Miners aren't very forthcoming about their locations for obvious reasons."[22] Because miners don't have a public-facing role, it's difficult to hold them accountable for their environmental footprint or, in most cases, even to know who they are. Brendan O'Connell from Patch suggested:

> *Miners are distributed around the world, often in regions with cheap and plentiful energy. Outside of regulation, the only pressure on miners to adopt clean energy is cost control. But in many parts of the world, fossil fuels are heavily subsidized and thus cheaper than renewable options. In challenging market conditions, mining operations run on thin margins, so it's unsurprising that we don't see significant investment in carbon removal from this cohort.*[23]

Second, miners aren't the only ones responsible for these emissions. The "work" of mining is a deliberately chosen consensus mechanism that allows a PoW blockchain to function; the onus is on a broader group of stakeholders. Miners help enable an entire blockchain ecosystem of cryptocurrencies, tokens, transactions, and smart contracts—and, by implication, all the participants who rely upon

It's natural that climate concerns related to NFTs have caused these players to shift their approach rapidly and search for more sustainable solutions.

it. So, just as blockchain benefits can accrue to a wide variety of participants, so too must that group shoulder some of the cost and responsibility for a blockchain's negative externalities. Unlike miners, many blockchain participants are highly visible and easy to identify.

Blockchains, like many other sectors, are forced to reckon with more scrutiny and pressure on the retail side of the business. The buck stops with those with purchasing power, said Alex Taylor: "That is the coal face. That is where the market activity happens, and where demand—and, in turn, load on the system—is created."[24] Retail is the leverage that accommodates consumer concerns and pushes them through the rest of the supply chain. For blockchains, NFT marketplaces are one of those highly visible participants. It's natural that climate concerns related to NFTs have caused these players to shift their approach rapidly and search for more sustainable solutions.

Regulators themselves, however, have had fewer qualms about putting restrictions on PoW mining. Several countries, such as Algeria, Bangladesh, China, Egypt, Iraq, Morocco, Qatar, and Tunisia, have cracked down on PoW mining.[25] In places like Kosovo, mining has been particularly problematic. Low-cost energy sources, subsidies, and political squabbles have consequently attracted bitcoin miners to Kosovo.[26] Some miners don't even pay for electricity. Pressures on the electrical grid are now forcing widespread crackdowns and a ban on crypto mining.[27]

One of the main drivers of change comes from within the ecosystem itself. Without explicit pressure, change doesn't happen. Society has a growing awareness of its obligation to make sound choices that minimize our impact on the environment. Making those obligations a reality is about voting with our feet, supporting those who accommodate sustainable practices,

and walking away from those who don't. It's also about being thoughtful and prudent about choices. Usually, that means digging beyond the surface to uncover the truth.

This prudence has parallels in many other environmental, social, and governance efforts, which must be wary of supply chain participants that bandy about empty marketing terms or engage in greenwashing or other deceptive activities. Instead, it's best to take a data-driven approach. Online calculators and published data make it possible to calculate our blockchain carbon footprint or access the impact of using one blockchain or sidechain over another. There's also a lot of work that's been done to address the complexity of carbon allocations, both for emissions and for abatement.

The Need for Prudent Policy

An interrelated element is policy and the growing number of countries banning or proposing to ban crypto mining. For example, Erik Thedéen, vice-chair of the European Securities and Markets Authority, has called upon the European Union to ban PoW mining and "nudge the industry" toward PoS. In his interview with the *Financial Times*, Thedéen said, "We need to have a discussion about shifting the industry to a more efficient technology." He did not call for a total ban of crypto."[28]

"This demonstrates a more sophisticated understanding of the ecosystem than the outright bans from 2017 to 2019, which conflated cryptocurrencies blockchains and proofs or consensus mechanisms, making it challenging for early blockchain PoS use cases focusing on environmental and sustainable energy and even making solutions illegal in some countries," said Katherine Foster, strategy advisor, The Digital Economist.[29] It also points to limits of shifting Bitcoin and other PoW mining to renewable sources because of the sheer energy supply required, even if based on renewables. "Bitcoin is now a national issue for Sweden because of the amount of renewable energy devoted to mining," said Thedéen.[30]

Ways to Manage Complexity

Complexity is hard. That's especially true of carbon emissions and sequestration. It's a deceptively complex topic. Si Chen of Open Source Strategies said, "The problem with climate is that it's cross border and cross industry."[31] Several intermediaries have arisen to help remove some of the complexity. Verification organizations assess the quality of carbon offset projects, for example. "One tonne of carbon doesn't always equal another tonne of carbon," said Brendan O'Connell. A lot depends on project quality. O'Connell, the crypto lead at Patch Technologies, explained:

> *The way the market deals with this is through variable pricing for carbon credits. On the low end, you can purchase a credit for $5 a tonne, which will have the least durability. On the high end, you can spend over $1,000 a tonne, which will offer a greater degree of certainty over the climate impact of the investment.*[32]

The analysis doesn't stop there. For carbon sequestration projects, there are key questions like whether there's a new net benefit and who gets to claim the credit for it. O'Connell said, "Another important consideration that impacts price is *additionality*, which is an assessment of whether the emissions would have been removed or avoided in the absence of carbon credit issuance."[33]

Intermediaries model all that complexity and come up with simple answers that inform our choices—like the ability to click a button that automatically offsets our carbon as part of a purchase. O'Connell offered this example: "Every time a transaction happens, you call our API and it spits out a carbon footprint assessment of that transaction. … You'll be able to see all of those characteristics to make a decision as to which of the projects you should be purchasing."[34]

Leading the NFT Transformation

All NFTs are not created equal. The process of how and where an NFT is minted, bid on, rendered, purchased, or transferred makes all the difference. This section looks at several of these decision points and makes recommendations that help ensure that the process is as sustainable as possible. This process boils down to six steps, each detailed in this section:

- Avoid PoW blockchains
- Look at the process end to end
- Pick a lightweight blockchain
- Seek innovative alternatives
- Offset (with verification) what's left
- Cement commitments

Avoid PoW Blockchains

The single biggest and easiest step is to avoid PoW blockchains. That means avoiding the Ethereum mainnet, which still accounts for the bulk (80%) of NFT market share by market capitalization, but which constitutes an even bigger percentage of overall emissions.[35] This simple step can reduce an NFT's carbon footprint by an order of magnitude. Until Ethereum PoS is up and running with proof of stake, it's difficult to recommend using this NFT carbon behemoth.

For those who already own an NFT collection on Ethereum, then simply leaving it at rest may be the best course of action. At present, moving an Ethereum based NFT collection to another blockchain will consume even more power, and so it's best to wait until proof of stake arrives. However, if a transaction is unavoidable, then moving it off the mainnet may be the best available approach, along with offsets to make the transaction carbon neutral. In fact, even if an Ethereum NFT is left at rest, the purchase of offsets is worth considering as a mechanism to offset the original process of minting and purchasing it, bringing an NFT into a carbon-neutral state.

The purchase of offsets is worth considering as a mechanism to offset the original process of minting and purchasing it, bringing an NFT into a carbon-neutral state.

Look at the Process End to End

Assessing the footprint of an NFT requires a broad holistic approach that looks at the full range of factors during a NFT's lifetime. Rather than narrowly focusing on the transaction costs of a sale, we must also consider the full range of NFT-related activities that touch the blockchain. That includes any on-chain bidding process, the minting and rendering of the NFT itself and any related contracts, and any activity or changes to the NFT contract during the period of ownership.

Accuracy means rolling up our sleeves on the implementation details. Si Chen said, "How do you measure the energy use of a blockchain and its climate impact? You would have to—if you're serious about it—measure it based on the actual compute cycles and energy that's being used, and know where the source of that energy comes from."[36] These factors also differ, depending on whether the NFT is a ERC-721 or ERC-1155 token. For example, ERC-1155 can improve efficiency via batched transactions. Under the strictest possible approach, some might consider an NFT at rest to be contributing to carbon emissions as part of this end-to-end process. That's because the value of the asset still benefits by the system of mining that keeps

WWF and Polygon

In February 2022, the World Wildlife Fund pulled the plug on a NFT fundraising effort in the United Kingdom: "We recognize that NFTs are a much debated issue, and we all have lots to learn about this new market, which is why we will now fully assess the impact of this trial and reflect on how we can best continue to innovate to engage our supporters."[37] The effort drew ire from WWF supporters who claimed that NFTs were damaging to the environment and that the WWF should not engage in such efforts.

Initially, the WWF responded that it had done its due diligence and was using Polygon, a layer 2 blockchain that boasted just 0.2 grams of CO_2 per transaction.[38] Critics maintained that this was not accurate, because Polygon's interface with Ethereum meant the true carbon footprint was far higher. *Digiconomist* delved into the details and suggested that, when Polygon's Ethereum interactions are allocated across Polygon's chain, the true CO_2 cost per transaction is closer to 430 grams of CO_2. That's much higher than the 0.2 grams claimed by the WWF—indeed, multiple sources suggested Polygon's per transaction footprint is under a gram—but even the *Digiconomist* value is a vast improvement over the 124 kilograms per transaction of Ethereum's network.[39] But should an Ethereum bridge and contracts really be allocated as CO_2 costs to a blockchain attached to it? That's a more complex question.

In hindsight, it's difficult to say whether diving into the details of the implementation would have made a difference to WWF's NFT plans.

If an NFT is minted on a sidechain, paid for in a currency that doesn't require a blockchain transaction (i.e., USD), and kept on the sidechain—then it doesn't require carbon-heavy Ethereum transactions at all. For a layer 2 solution like Polygon, which periodically submits checkpoints on the mainchain, the true carbon footprint of a transaction may depend on the specific NFT implementation and how far it goes beyond checkpoints. In hindsight, it's difficult to say whether diving into the details of the implementation would have made a difference to WWF's NFT plans. Nevertheless, prior to a rollout, it always pays to get "under the hood" of the system in use to avoid any unpleasant surprises. Equally important is laying the groundwork with a process of open communication that offers an opportunity for critical discussion and respectful dialogue without the looming pressure of a decision that has already been made.

the blockchain operable and secure. In practice, many carbon allocation systems are not quite this strict; but for those seeking the least possible footprint, it's an approach worth consideration.

Pick a Lightweight Blockchain

Ethereum isn't the only game in town when it comes to NFT-capable blockchains. From a 95 percent share in 2021, Ethereum is now 80 percent of NFTs.[40] Solana, though it has been subject to numerous outages over the past year, has proven to be a hotbed of NFT activity. Solana surpassed $1 billion in all-time market volume at the beginning of 2022, and *DappRadar* counts Magic Eden (an NFT marketplace on Solana) as the tenth most popular Dapp ranked by number of users.[41] With Solana currently operating at approximately 2,500 transactions per second, it's both a rapid and economic way to conduct NFT and smart contract transactions using its proof-of-history consensus mechanism. Other currently operational PoS blockchains such as Cardano or Tezos are also worthy of consideration. Some see a broader shift underway where layer 2 does most of the transaction volume, and "layer 1 will ultimately evolve, due to expense, into what's called a *settlement chain*."[42]

Seek Innovative Alternatives

For the smallest possible blockchain carbon footprint, even popular PoS blockchains may not be enough. Upper limits on transactions per second and redundancy of verifiers all add up to slightly more carbon. Taking transactions off the mainchain and onto low carbon-footprint permissioned chains, layer 2 networks, or sidechains removes some of that overhead and reduces energy requirements even further. "These layer twos are fairly efficient … . You don't need a lot of servers to run it," Said one blockchain engineer.[43] (See "WWF and Polygon" sidebar for an example of layer 2.)

Charlie Robbins is vice president of engineering at Candy Digital, a company that helps big brands like Major League Baseball leverage NFTs. To lower its footprint, Candy Digital uses an EVM-compatible sidechain called the Palm network. In the ideal situation, said

Robbins, "You could end up with a model where minting an NFT is less energy than making a Google search."[44] That uses so little energy that most people wouldn't bat an eyelash at it, Robbins said, adding that he believes Candy Digital will reach that point within the next year.[45]

Daniel Heyman, co-founder and CEO of Palm NFT Studio, was formerly at ConsenSys where he worked on Hyperledger Besu, an enterprise-friendly blockchain solution engineered deliberately with efficiency in mind. Heyman understood the high transaction costs and environmental consequences of working with NFTs on blockchains like Ethereum, and so Hyperledger Besu was a natural choice to bring a better NFT solution to market. Hyperledger Besu is built with a modular design and supports the EVM while allowing for both PoW and PoA consensus mechanisms.[46] This flexibility means it can interface with both public and permissioned blockchains. Said Heyman, "I believed we needed a home within the broader Ethereum ecosystem for NFTs to trade in a way that was environmentally sustainable, scalable, and cheap."[47] According to Patch Technologies, the PoA consensus mechanism used by the Palm network is 99.9 percent more efficient than proof of work.[48] As the industry matures, verification of CO_2 footprints by third parties will also be a key to encouraging adoption of low-carbon NFT platforms.

However, efficiency isn't the only consideration. Convincing someone to make an NFT purchase via a new or unfamiliar blockchain or sidechain is a nontrivial undertaking. It helps to have adoption by familiar NFT brands, but the technology and its longevity is important too. There are methods to address these concerns, for example a bridge that allows purchased NFTs to be moved onto mainnet Ethereum (though again, exercising that option has a costly carbon footprint). Julian Perez, operations analyst at Palm NFT Studio, explained how it works: "People can use the bridge to Ethereum mainnet if they want to … . This bridge works in both directions for NFTs and for tokens."[49] NFT holders have the confidence that the Palm network can connect to both permissioned and public blockchains, and their NFTs can (optionally) have exposure to liquidity on a major mainnet blockchain. While moving NFTs onto Ethereum is a poor value proposition in terms of both cost and environmental footprint, the ability to port our NFTs is a valuable confidence-inspiring feature, even if that option is never exercised. However, any specific implementation must carefully weigh its decision about offering conversion to the mainnet or Ethereum as a payment option. By engaging with Ethereum mainnet contracts, the lightweight carbon footprint of a sidechain can easily be lost.

Another key blockchain feature often touted by supporters is strong ownership rights. NFTs open up avenues for strong ownership rights over digital assets. Yet, for brands that are already vested in managing their IP within existing legal regimes, strong ownership rights aren't the only hook. Dan Heyman said, "It's a way of giving, it's activating and engaging their most loyal fans and creating that community. NFTs, and blockchains more generally, are social coordination devices—they are ways to

really engage communities."[50] So ownership rights are more a means to an end. Dan Heyman suggests brands and IP owners can, "reimagine the digital relationship between creator and fan—from a rental one with streaming and social media—to an ownership based one, where fans can have a piece of what they love and they can show it off to their friends can speak to who they are, and form a part of their identity."[51] That's a much broader range of opportunities than digital artwork. It requires an infrastructure with efficiency, flexibility, and scale, something that enables the use of NFTs in a wide range of communities in online and even physical environments. Verified energy and climate disclosures can act as a valuable new layer to any business transaction. Today those use cases are all but impossible on PoW chains like Ethereum.

Use Verifiable Offsets

Sustainable practices for NFTs start with reduction. "There are some industries where low carbon options are simply not available. Blockchain is not one of them," said Chen.[52] Once the limits of reducing impact are reached, the remaining impact can be offset, allowing us to reach net-zero or better. Yet, the use of offsets comes with an important caveat and is not a substitute for reduction. According to Chen:

> *The legitimacy of offsets relies on economic assumptions such as "additionality," meaning that a project would not have occurred without the purchase of the offsets. Because many offset projects could have been viable without the offsets, they are not truly "additional." Offsets from these projects would be available at very cheap prices. This means it would be cheaper to buy offsets rather than do the hard and expensive work of real decarbonization.*[53]

Offset projects can include a wide range of activities, from planting new forests to capturing methane gas from landfills. Yet it's important we don't treat offsets as a shortcut around reduction. Brendan O'Connell of Patch said, "We're not going to offset ourselves out of a climate crisis."[54] Energy intensive PoW chains can't simply buy themselves out of the problem. Charlie Robbins of Candy Digital added that kind of thinking "is based on a logical fallacy that any damage that is done can be undone, and that's simply not true."[55]

"There are some industries where low carbon options are simply not available. Blockchain is not one of them."

— SAI CHEN

Carbon offsets still play a key role, allowing organizations and individuals to have a small (or even negative) carbon footprint after they've made whatever reductions they can. However, the array of offset projects can lead to claims of greenwashing. It is vital that robust, certified initiatives are at the core of these activities. Measured, verified, and certified offsets allow a price to be placed on carbon intensive activities providing companies and businesses with a way to incorporate these in their budgets. That awareness is key. Brendan O'Connell said, "It becomes a line item in their operating expenses, and businesses are really good at minimizing costs."[56] Charlie Robbins concurred, "I don't think it's a band aid. I think that it's an important part of an overall narrative of sustainability."[57]

Investing in offsets also provides a final benefit: access to capital for robust carbon offset projects that offer additional environmental and developmental impacts. For example, mangroves or regenerative agricultural projects can not only allow for carbon sinks but support positive impacts on water, help farmers adapt to climate change, and benefit communities and marginalized

peoples. Today, offsets can be expensive, often limited by the scale they can achieve and the challenges and costs of monitoring, reporting, verifying, and certifying, for example. Contributing to offsets helps bring new scale and efficiencies to carbon offset projects, a cycle of positive reinforcement that makes offsets more affordable, which in turn fosters additional cycles of scale and investment. Brendan O'Connell of Patch Technologies suggested that, by getting high quality offset projects to scale, "they can actually decrease the price of carbon."[58]

Cement Commitments

While technology choices are important, change can't happen without bringing stakeholders onboard. In many cases, that starts with a commitment by ecosystem stakeholders. One successful NFT initiative called CarbonDrop engaged key stakeholders early, in the process of the NFT auction and the choices about how it would be implemented. This engagement, right from the start, was key to getting participants onboard and committed to the process. Together the group agreed to "Seven Steps NFT Art Platforms Can Take on Climate." Stakeholder engagement from the beginning helps pave the way for a project and reduces the risk of potential knee-jerk negative responses via social media.

Often, internal commitment from an individual or an organization helps get the ball rolling, too. For organizations, that can take the form of what CarbonDrop described as, "open climate announcement or press statement about the adopted steps and science based verified climate commitments."[59] These kinds of announcements proactively address any concerns and set examples for others.[60] CarbonDrop suggested that, particularly for corporations, cementing commitment also starts with a program of measurement as well as pledging specific targets: "Initiate corporate carbon footprinting measures and tools for the platform and parent companies, along with commitments to achieving net-zero corporate emissions under industry standards such as the Climate Pledge and science-based targets, in line with the Paris Agreement."[61]

Conclusion: The Path to Sustainable NFTs

The original question driving this report was, "Are carbon-friendly NFTs possible"? The answer is a definitive yes, *if* the entities issuing or using NFTs are prepared to dig into the implementation details and make the right series of technology and blockchain choices. The vast energy requirements of the first generation of Ethereum NFTs are no longer a limiting factor. Many eco-friendly options already exist and, in this rapidly evolving landscape, the future will only get better as some of the worst offenders move to proof of stake, not to mention the growing number of other emerging alternatives.

With that knowledge in hand, organizations can consider what really matters—what do they mean to accomplish with NFTs, what near types of engagement and community do they facilitate? NFTs are incredibly powerful tools to transform how we engage and interact with one another. Those values are ultimately what should drive the effort. Brendan O'Connell put it best, saying we have "this grand opportunity to build a truly sustainable economic system."[62] NFTs can offer exciting climate-friendly options for a wide variety of projects. NFTs and smart contracts may also unlock valuable new strategies and options for tackling climate change itself. Innovators are already exploring the securitization of carbon, the engagement and mobilization of citizens, and even endowing nature itself with rights and protections mediated by smart contracts. The choices are up to you.

A CONSERVATIONIST'S PERSPECTIVE ON...

PROOF OF WORK (PoW) VS. PROOF OF STAKE (PoS)

PROOF OF WHAT?!

A blockchain is made of **NODES**, each node is one complete copy of the distributed ledger.

To complete a transaction and add it to the blockchain, a **CONSENSUS** between all nodes must be achieved.

PoW and **PoS** are

CONSENSUS MECHANISMS

Different networks use different consensus mechanisms to establish trust in the ledger.

BITCOIN
ETHEREUM

POLYGON
SOLANA
CARDANO

Reaching consensus: **HOW** is a transaction verified?

PoW: COMPUTATIONAL POWER

'Miners' race to complete the complex cryptographic puzzles needed using computer processing power. Speed is rewarded.

PoS: CURRENCY POWER

Crypto is set aside as a guarantee of trustworthiness. These 'stakers' are randomly chosen to complete a verification process. Reward is proportional to amount & time staked.

The **ENVIRONMENTAL IMPACT** of a blockchain depends on the energy used to reach consensus.

A typical PoW transaction uses **more energy than a US household uses in 8 days.**

PoW:
Computers racing to solve the same problem is **ENERGY INEFFICIENT** and **INTENSIVE.**

PoS:
When speed isn't a factor, energy use is **MINIMAL.**

A typical PoS transaction uses **less energy than making 2 Google searches.**

KEEP IN MIND

PoW and PoS are not the only options.

- Proof of Good
- Pure Proof of Stake
- Proof of Authority
- Proof of Activity
- Proof of History
- Proof of Capacity
- AND MORE!

ALL mechanisms have trade-offs.

- Security
- Decentralisation
- Scalability
- Energy use
- Accessibility

tldr

Blockchain technology is not inherently bad for the environment; the consensus mechanism chosen determines environmental and social impact.

Source data for several graphics courtesy of Sasha Sebright and Adrian Dellecker of tldr.earth.

Acknowledgments

This report is the result of numerous interviews conducted from November 2021 to March 2022. We thank the following people who participated in the interview process and shared thoughtful and candid perspectives and insights:

Si Chen, President, Open Source Strategies Inc.

Daniel Heyman, Co-founder and Chief Executive Officer, Palm NFT Studio

Brendan O'Connell, Crypto Lead, Patch Technologies Inc.

Julian Perez, Operations Analyst, Palm NFT Studio

Johnna Powell, Global Co-head, ConsenSys NFT

Charlie Robbins, Vice President of Engineering, Candy Digital

Alex Taylor, Co-founder, Offsetra

Special thanks to project advisor Katherine Foster, Social Alpha Foundation and The Digital Economist, whose oversight and contributions to this research effort were invaluable. Thanks also to community leaders and practitioners who reviewed this report and provided valuable feedback, including Jo Howard and Cat Knoerr of Palm NFT Studio, Christian Averill of Quality Produce, and JT Rose of ConsenSys. Conservation leaders Adrian Dellecker and Sasha Sebright of tldr.earth provided inspiration and permissions to recreate visuals used in this report; for their collaboration, we are grateful. Thanks also to the Linux Foundation and Hyperledger Foundation teams, including Sean Bohan, David Boswell, Hilary Carter, Dorothy Cheng, Alena Davis, Michael Dolan, Emily Fisher, Julian Gordon, Lawrence Hecht, Ry Jones, Jerry Lee, Carolyn Lehman, Hart Montgomery, Christina Oliviero, Karen Ottoni, Jason Perlow, Melissa Schmidt, Tomaz Sedej, Chip Stuart, Benjamin Thomas, Jessie Wang, and Min Yu, for their supportive roles in this project's development.

About the Author

Alan Majer is the founder of Good Robot. For the first half of his career, Alan worked as a technology researcher and writer, helping to identify cutting-edge technology and business innovations. Today, Alan works with technology hands on, exploring the potential of artificial intelligence, robotics, blockchain, and the metaverse. The result is exciting new opportunities to innovate and transform user experiences, and the ability to combine strategy and research activities with a real-world approach to their implementation. Alan is an active member of the local "maker" scene, frequenting spaces like HackLab.TO and InterAccess. He holds an MBA from McGill University.

Disclaimer

This report is provided “as is.” The Linux Foundation and its authors, contributors, and sponsors expressly disclaim any warranties (express, implied, or otherwise), including implied warranties of merchantability, noninfringement, fitness for a particular purpose, or title, related to this report. In no event will the Linux Foundation and its authors, contributors, and sponsors be liable to any other party for lost profits or any form of indirect, special, incidental, or consequential damages of any character from any causes of action of any kind with respect to this report, whether based on breach of contract, tort (including negligence), or otherwise, and whether they have been advised of the possibility of such damage. Sponsorship of the creation of this report does not constitute an endorsement of its findings by any of its sponsors.

Endnotes

1 Carl Beekhuizen, "Ethereum's Energy Usage Will Soon Decrease by ~99.95%," *Ethereum Foundation Blog*, 18 May 2021, https://blog.ethereum.org/2021/05/18/country-power-no-more.

1 "IPwe and IBM Seek to Transform Corporate Patents with Next Generation NFTs Using IBM Blockchain," Press Release, IBM Corp., 20 April 2021, https://newsroom.ibm.com/2021-04-20-IPwe-and-IBM-Seek-to-Transform-Corporate-Patents-With-Next-Generation-NFTs-Using-IBM-Blockchain.

3 "The Chainalysis 2021 NFT Market Report: Everything You Need to Know About the NFT Market and Its Most Successful Collectors," Chainalysis Pte. Ltd., updated Jan. 2022, https://go.chainalysis.com/rs/503-FAP-074/images/Chainalysis%20NFT%20Market%20Report.pdf. This report covers ERC-721 and ERC-1155 (i.e., Ethereum only) NFTs and may include transactions that are not purchases. NonFungible.com gives a more conservative figure of $17.7 billion traded in its "Yearly NFT Market Report," 2021, https://www.nonfungible.com/reports/2021/en/yearly-nft-market-report.

4 Scott Reyburn, "Art's NFT Question: Next Frontier in Trading, or a New Form of Tulip?" New York Times, 30 March 2021, updated 29 April 2021, https://www.nytimes.com/2021/03/30/arts/design/nft-bubble.html.

5 Avivah Litan, "Hype Cycle for Blockchain 2021; More Action than Hype," Gartner Blog, Gartner Inc., 14 July 2021, https://blogs.gartner.com/avivah-litan/2021/07/14/hype-cycle-for-blockchain-2021-more-action-than-hype/.

6 Some have used these instruments to perpetrate fraud on a massive scale, such as $25 billion in counterfeit US bearer bonds: https://www.investmentexecutive.com/news/industry-news/rcmp-seize-25-billion-in-fake-u-s-bearer-bonds/.

7 Daniel Heyman, interviewed by Alan Majer, 14 Feb. 2022.

8 Daniel Heyman, interviewed by Alan Majer, 14 Feb. 2022.

9 "Carbon Footprint," Annualized Total Bitcoin Footprints, Digiconomist.net, as of 24 March 2022, https://digiconomist.net/bitcoin-energy-consumption.

10 Philip Rosedale (@philiprosedale), "Buying bitcoin and drive the price up 10% is the same as if @Tesla had put 800,000 gasoline-powered cars back on the road, forever. The math:," Twitter, 10 Feb. 2021 (3:12 PM), https://twitter.com/philiprosedale/status/1359596124932198400. This tweet sparked heavy debate on Twitter. The assumptions behind it are stated, allowing users to draw their own conclusions. Regardless of whether the cost is overstated, the underlying observation appears to be correct: increases in bitcoin price are correlated with a higher overall carbon footprint.

11 Christine Kim, "The Rise of ASICs: A Step-by-Step History of Bitcoin Mining," CoinDesk Insights, CoinDesk, 26 April 2020, updated 14 Sept. 2021, https://www.coindesk.com/tech/2020/04/26/the-rise-of-asics-a-step-by-step-history-of-bitcoin-mining/. CPU stands for "central processing unit."

12 "Carbon Footprint," Annualized Total Ethereum Footprints, Digiconomist, as of 24 March 2022, https://digiconomist.net/ethereum-energy-consumption. However, other sources suggest that it may be as low as 10 megatons annually, and we have elected the more conservative (i.e., higher carbon footprint) number to share in this report.

13 "The Merge," Ethereum, Ethereum Foundation, updated 23 March 2022, https://ethereum.org/en/upgrades/merge/.

14 Moritz Seibert, "Bitcoin and Ethereum Carbon Footprints—Part 1," Blog, Medium.com, 21 March 2021, https://moritz-seibert.medium.com/bitcoin-and-ethereum-carbon-footprints-a8d7f7871f5a. We updated the analysis in Seibert's post based on the combined total of 177.01 Mt of CO2 (Bitcoin's 114.06 Mt and Ethereum's 62.69 Mt compared to the 40 Mt and 14 Mt that Seibert used to yield .11%), which is 0.36% of global CO2).

15 "Cardano," CoinMarketCap, as of 25 March 2022, https://coinmarketcap.com/currencies/cardano/.

16 "Ethereum vs. Cardano," Artano, n.d., https://artano.io/efficiency/.

17 "Are 'Eco-Friendly' NFTs as Green as Their Creators Claim?" MusicAlly, Music Ally Ltd., 10 Feb. 2022, https://musically.com/2022/02/10/are-eco-friendly-nfts-green/.

18 "The Beacon Chain," Ethereum, Ethereum Foundation, updated 23 March 2022, https://ethereum.org/en/upgrades/beacon-chain/.

19 Bhushan Akolkar, "Vitalik Buterin Talks about What's Ahead for Ethereum 2.0 in 2022," Coinspeaker, 5 Jan. 2022, https://www.coinspeaker.com/vitalik-buterin-ethereum-2-0-2022/.

20 Johnna Powell, email to Alan Majer, 17 March 2022.

21 We say "most" PoW blockchains because future PoW blockchains may contribute valuable work (e.g., storing files, running models/simulations, etc.) instead of consuming energy to solve puzzles.

22 Alex Taylor, interviewed by Alan Majer, 11 Jan. 2022.

23 Brendan O'Connell, interviewed by Alan Majer, 5 Jan. 2022.

24 Alex Taylor, interviewed by Alan Majer, 11 Jan. 2022. Coal face here refers to the exposed surface of coal in a mine.

25 Abby Lee Hood, "Another Entire Country Just Banned Crypto Mining," Earth & Energy, Futurism, 9 Jan. 2022, https://futurism.com/kosovo-crypto-ban/amp.

26 Daniel Boffey, "Panic as Kosovo Pulls the Plug on Its Energy-Guzzling Bitcoin Miners," The Guardian, 16 Jan. 2022, https://www.theguardian.com/

technology/2022/jan/16/panic-as-kosovo-pulls-the-plug-on-its-energy-guzzling-bitcoin-miners.

27 Daniel Boffey, "Panic as Kosovo Pulls the Plug on Its Energy-Guzzling Bitcoin Miners."

28 Eva Szalay, "EU Should Ban Energy-Intensive Mode of Crypto Mining, Regulator Says," Financial Times, 19 Jan. 2022, https://www.ft.com/content/8a29b412-348d-4f73-8af4-1f38e69f28cf.

29 Katherine Foster, communication with Alan Majer, 25 Mar. 2022.

30 Eva Szalay, "EU Should Ban Energy-Intensive Mode of Crypto Mining, Regulator Says."

31 Si Chen, interviewed by Alan Majer, 16 Dec. 2021.

32 Brendan O'Connell, interviewed by Alan Majer, 5 Jan. 2022.

33 Brendan O'Connell, interviewed by Alan Majer, 5 Jan. 2022.

34 Brendan O'Connell, interviewed by Alan Majer, 5 Jan. 2022.

35 Will Canny, "J.P.Morgan Says Ethereum Is Losing NFT Market Share to Solana," CoinDesk, 19 Jan. 2022, https://www.coindesk.com/business/2022/01/19/jpmorgan-says-ethereum-is-losing-nft-market-share-to-solana.

36 Si Chen, interviewed by Alan Majer, 16 Dec. 2021.

37 World Wildlife Fund UK, "NFT Statement," Updates, 4 Feb. 2022, https://www.wwf.org.uk/updates/nft-statement.

38 "The Carbon Footprint of Polygon," Digiconomist, 4 Feb. 2022, https://digiconomist.net/the-carbon-footprint-of-polygon/.

39 "The Carbon Footprint of Polygon," Digiconomist, 4 Feb. 2022.

40 Will Canny, "J.P.Morgan Says Ethereum Is Losing NFT Market Share to Solana," CoinDesk, 19 Jan. 2022.

41 MK Manoylov, "Solana NFT Total Sales Volume Crosses $1 Billion," TheBlockCrypto, Block Crypto Inc., 19 Jan. 2022, https://www.theblockcrypto.com/linked/130874/solana-nft-total-sales-volume-crosses-1-billion; "Top Blockchain Dapps," DappRadar, as of 23 March 2022, https://dappradar.com/rankings.

42 Blockchain engineer, interviewed by Alan Majer, 17 Dec. 2021.

43 Blockchain engineer, interviewed by Alan Majer, 17 Dec. 2021.

44 Charlie Robbins, interviewed by Alan Majer, 1 Feb. 2022.

45 Charlie Robbins, interviewed by Alan Majer, 1 Feb. 2022.

46 Rob Dawson and Meredith Baxter, "Announcing Hyperledger Besu," Hyperledger Blog, 29 Aug. 2019, https://www.hyperledger.org/blog/2019/08/29/announcing-hyperledger-besu.

47 Daniel Heyman, interviewed by Alan Majer, 14 Feb. 2022.

48 Palm uses IBFT 2.0. "Patch Crypto Carbon Accounting Methodology," PatchTech, 19 July 2021, updated 15 Sept. 2021, https://patchtech.notion.site/Patch-Crypto-Carbon-Accounting-Methodology-f25e2a8dd34e4f55bbd92c9ee38516f9.

49 Julian Perez, interviewed by Alan Majer, 8 Feb. 2022.

50 Daniel Heyman, interviewed by Alan Majer, 14 Feb. 2022.

51 Daniel Heyman, interviewed by Alan Majer, 14 Feb. 2022.

52 Si Chen, communication with Alan Majer, 22–23 Feb. 2022.

53 Si Chen, communication with Alan Majer, 22–23 Feb. 2022.

54 Brendan O'Connell, interviewed by Alan Majer, 5 Jan. 2022.

55 Charlie Robbins, interviewed by Alan Majer, 1 Feb. 2022.

56 Brendan O'Connell, interviewed by Alan Majer, 5 Jan. 2022.

57 Charlie Robbins, interviewed by Alan Majer, 1 Feb. 2022.

58 Brendan O'Connell, interviewed by Alan Majer, 5 Jan. 2022.

59 "Seven Steps NFT Art Platforms Can Take on Climate," CarbonDrop, n.d., https://www.carbondrop.art/climate-suggestions.

60 "Seven Steps NFT Art Platforms Can Take on Climate," CarbonDrop, n.d.

61 "Seven Steps NFT Art Platforms Can Take on Climate," CarbonDrop, n.d.

62 Brendan O'Connell, interviewed by Alan Majer, 5 Jan. 2022.

Founded in 2021, Linux Foundation Research explores the growing scale of open source collaboration, providing insight into emerging technology trends, best practices, and the global impact of open source projects. Through leveraging project databases and networks, and a commitment to best practices in quantitative and qualitative methodologies, Linux Foundation Research is creating the go-to library for open source insights for the benefit of organizations the world over.

To reference the work, please cite as follows: Alan Majer, “The Carbon Footprint of NFTs: Not All Blockchains Are Created Equal,” foreword by Daniela Barbosa, The Linux Foundation, April 2022