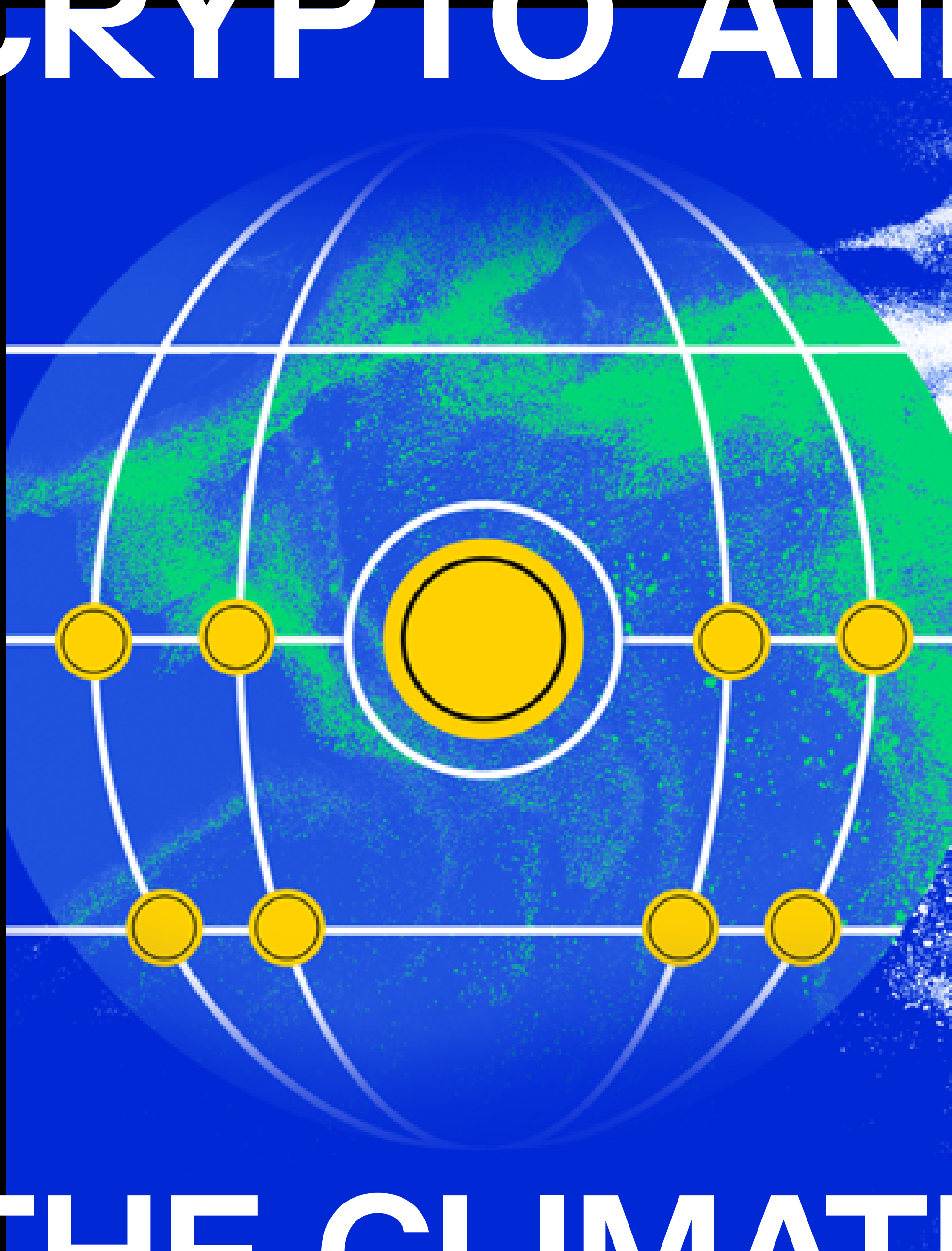
coinbase INSTITUTE

CRYPTO AND THE CLIMATE



EXECUTIVE SUMMARY

We live in a world that is increasingly digitalized: most economic transactions and social interactions today occur remotely through the internet. The rapid digitalization of our lives also coincides with the growth of large social media and financial service companies with significant market power. Nevertheless, the financial infrastructure supporting economic exchanges is still for the most part analog, tethered to a past that was tied to the physical processing of transactions. Compared to the internet, our financial services infrastructure is slow, inefficient, and siloed, creating advantages for some over others. In the last decade, the adoption of blockchain technology has challenged many of the routine inefficiencies of our financial sector. Unlike the historical financial transactions infrastructure, crypto is built on the internet. And so unlike the historical infrastructure, it can provide borderless, seamless, and nearly-instantaneous settlements that are scalable for everyone to use, not just for a few centralized financial institutions.

To achieve this new infrastructure, crypto relies on a distributed network of computers, connected over the internet, that constantly validate economic transactions and financial contracts. Because these computers (and the people who run them) do not know each other and have no relationship with each other, underpinning the technology are consensus mechanisms that incentivize anonymous participants to act honestly. The first and most popular consensus method is called “Proof of Work” (PoW), where participants in the network compete to be the first to solve cryptographic puzzles. In return for their efforts, participants receive a newly-minted amount of cryptocurrency, known as a mining reward. This PoW process achieves two objectives: (i) it allows anyone to validate transactions; and (ii) it secures the network against malicious attempts to modify the transaction history. In other words, we do not need to trust a third party with our financial information, and we do not have to trust that they will execute our transactions faithfully.

With the recent and rapid rise in cryptocurrency value, the incentives for validators have skyrocketed. Currently, large public and private companies spend hundreds of millions of dollars every year to build mining facilities that operate 24/7 to solve cryptographic puzzles. Running these facilities requires vast amounts of electricity. The latest estimate is that Bitcoin mining consumes as much electricity as all refrigerators in the United States. Or that its consumption is nearly equivalent to that of Thailand or Malaysia. To those who don’t use crypto, this consumption seems nothing but wasteful.

But for crypto users, they think that this energy consumption is a fair price to pay for securing this new, more efficient, and more inclusive financial system, just as energy consumption by banks and other traditional financial institutions is accepted as a necessary cost of doing business. Or in the same way as using a refrigerator to keep our food cold and safe is worth the price of the electricity. PoW secures crypto against hacker attacks that could undermine the accuracy of transactions on the blockchain. It is currently estimated that hacking the Bitcoin blockchain would cost over $13B,[1] a figure that is high enough to make the transactions recorded on it basically immutable. The market design of PoW ensures that as these networks become more valuable, more is spent to secure them against malicious attacks.

[1] Eqonex, https://learn.eqonex.com/news/what-51-attack-and-how-much-would-it-cost

In addition to enhancing network security, PoW has additional attractive features for the electrical grid:

(i) its energy consumption has a steady base load, with a highly predictable demand;
(ii) it is an interruptible load, with the ability to switch off at a moment's notice; and
(iii) it can be located very close to the energy source.

Power grids benefit from users with base loads, as they can plan for and guarantee power days or even months in advance, unlike heating and air-conditioning units. Being interruptible enhances PoW as compared to other energy demands because power grids, when they're overtaxed, can ask miners to dial down or even turn off their operations to level off demand. This means that when there is a demand spike (e.g., heat wave) or supply shortage (e.g., loss of wind), power grids can interrupt miners' operations without adverse business impacts, and without having to turn on fossil-fueled "peaker" plants to supplement the demand spike. This is not something we can do with data centers and hospitals. And finally, the portability of mining operations allows them to divert excess energy that would otherwise be unused, or worse, "flared." Flaring is the environmentally harmful procedure of burning natural gas when an oil drilling company accidentally hits a natural gas formation and lacks a pipeline to harvest the gas. By placing their operations near these operations, PoW miners can help divert the gas to power their equipment. Preliminary studies estimate that such gas flaring recapture can reduce carbon emissions by 63%.

In addition to these innovative design features for electricity consumption, crypto is continuing to innovate to become more energy efficient, further driving down operating costs. Crypto developers have adopted new consensus mechanisms like Proof of Stake (PoS), which can use up to 99% less energy than the initial PoW implementations. The large majority of new crypto assets coming online are PoS-based, and their market share has been increasing over time. As crypto technology continues to become more energy efficient, the climate impact of crypto transactions will decline significantly over time.

Both the underlying design features and the rate of crypto's innovations in energy efficiency greatly surpass anything comparable in other industries.

This primer assesses the current state of crypto and the climate. Part 1 explores the energy use framework underlying crypto, with an emphasis on understanding Proof of Work. Part 2 reviews the attempts to assess the energy consumption of Bitcoin, and explains the challenges in agreeing on any assessment. Part 3 explores crypto's carbon footprint, including its use of renewable energy sources and other forms of consensus mechanisms. The conclusion identifies that crypto is innovating in sustainable energy use dramatically faster than any other legacy industry, and maps out areas for additional research, including the emerging potential for crypto and the blockchain to benefit the climate and support sustainable growth.

PART 1

How Cryptocurrencies Use Energy

A defining feature of cryptocurrencies is its decentralization. Almost all companies and institutions, from the Federal Reserve, to banks, insurance companies, social media companies, hospitals, security exchanges, and government agencies, are centralized entities where transactions and economic exchanges are recorded in a central ledger, owned and governed by a single party. This system leaves their ledgers extremely vulnerable to security breaches – a hacker only needs a single point of entry to tamper with or alter the ledger – and makes it very costly to guard against mistakes.

Instead, cryptocurrencies rely on a decentralized ledger, also called a blockchain, to approve or reject transactions. At a basic level, blockchain technology works by creating a chain of linked “blocks” that encode a sequence of transactions. It involves contributions from thousands of participants around the world connected anonymously in a peer-to-peer (P2P) network, working constantly to validate blockchain transactions and appending them to a chain of transaction blocks. Unlike centralized ledgers, where the central party approves or rejects the validity of transactions, a blockchain relies on the participants reaching a consensus on the validity of transactions. The most popular consensus mechanism in cryptocurrencies is Proof of Work; it is also the most controversial because of climate concerns.

Proof of Work

Proof of Work was developed to validate Bitcoin transactions and it was the first decentralized consensus mechanism. Most consensus mechanisms follow a majority rule, where a transaction is approved if a majority of the participants agrees that it is valid. But one of the defining features of cryptocurrencies is that they are permissionless, decentralized networks, meaning that anyone can join the network anonymously. Without any safeguards, such a network would be particularly vulnerable to malicious participants creating and controlling multiple anonymous nodes, manipulating the voting process, and altering the transaction ledger.

With a PoW consensus, however, participants (also called miners) compete with each other to solve a cryptographic puzzle. The first miner who solves the puzzle is selected to add a new block of transactions to the blockchain ledger, and the other miners verify that the transaction included in the new block is valid. The winner of the competition receives a mining reward that is predetermined by the network, along with the transaction fees paid by the originators of the transactions.

A critical feature of the Bitcoin PoW consensus mechanism is that the time between blocks is designed to average 10 minutes. With technological advances in hardware and software, solving the cryptographic puzzle would get easier over time if all else remained equal. However, with Bitcoin PoW, to keep the time between blocks at 10 minutes, the more miners who enter the competition, the harder it becomes to solve the puzzle. This is one of the safeguards built into the consensus mechanism to deter malicious actors: the cost of time and operations is high for each individual, and quickly becomes impossibly high if an actor attempts to alter the other participants' validations.

As Bitcoin and other cryptocurrencies become more valuable, more participants are incentivized to join the network of validators, buy expensive electronic hardware, and consume electricity to attempt to solve these cryptographic puzzles. With the value of Bitcoin today, a vast network of individuals, private enterprises, and public companies have built large data centers to such puzzles and earn the mining rewards. The trial-and-error process to solve these cryptographic puzzles requires specialized machines that are constantly running, as well as cooling power to prevent overheating. Currently, the entire Bitcoin network hashes 200 quintillion(10^18) hashes every second, which is a measurement of the attempts to solve the puzzles on the Bitcoin network.

The electricity consumed in the PoW process is necessary to secure the transactions in the chain and makes them practically immutable. For the history of transactions to be re-written, an actor would have to control more than 50% of the computing power of the network (a so-called "51% attack"), which would be prohibitively expensive, at over $13 billion.[2] This electricity consumed is part of the price to be paid for not having to rely on and pay centralized entities, such as banks, exchanges, and other intermediaries.

[2] Eqonex, https://learn.eqonex.com/news/what-51-attack-and-how-much-would-it-cost

Another way to consider the price to secure transactions through the PoW process is to review the value that society has assigned to cryptocurrencies: During the early years of crypto in 2010, the value of Bitcoin was very low, and thus few participants were incentivized to solve these cryptographic puzzles. The energy consumed by the network was low, but the network was also more vulnerable to attack. But because Bitcoin was not popular nor valuable, few had the desire or incentive to manipulate transactions. As crypto prices increased, more miners joined the network, and operated bigger and bigger data centers. The competition among miners, and the energy consumed in the process, makes the network more secure because it has become significantly more complex. All of this is proportional to the high value that society has assigned to crypto transactions.

PART 2

Assessing Crypto's Energy Use

Critics often cite statistics that Bitcoin mining alone consumes more energy than many countries.[3] But when it comes to mining, it is difficult to quantify the precise amount of energy involved. According to many energy experts, "there is currently no reliable, verifiable way" to measure the electricity used in crypto mining.[4] Analysts can easily calculate the total network hashrate (the measurement of calculations performed to verify transactions and perform the encryption that secures the network), but extrapolating the energy use without knowing the number of active computers and their energy efficiency leads to very imprecise estimates.[5] Historically, studies have relied on assumptions about mining computer networks to calculate the number of Watt-hours consumed per Gigahash/sec. But critics argue that this approach fails to account for factors such as the carbon footprint of building and deploying the computer hardware, the reliability of the machines used, and the cooling costs. Because different estimates rely on different assumptions, we are left with a "wide set of energy consumption estimates that strongly deviate from one another."[6]

[3] Cambridge Bitcoin Electricity Consumption Index (CBECI), https://ccaf.io/cbeci/index/comparisons

[4] CNBC, https://www.cnbc.com/2017/12/21/no-bitcoin-is-likely-not-going-to-consume-all-the-worlds -energy-in-2020.html

[5] Digiconomist, https://digiconomist.net/bitcoin-energy-consumption/

[6] Id.

Further, it is important to distinguish between energy use and carbon footprint. Because two processes may have the same energy use does not mean they will have the same carbon footprint. If one process relies more heavily on sustainable energy sources, its carbon footprint will be smaller than the other process with the equivalent energy consumption. In other words, a process's energy use alone is an incomplete picture without also knowing that process's energy mix. More on this in Section 3.

Most analyses of crypto's energy use focus on the proof of work mining of Bitcoin, which has the biggest market capitalization of any cryptocurrency. Bitcoin's annual energy consumption is estimated at between 121[7] -143[8] terawatt hours annually, which is greater than the energy consumption of many small- and medium-sized countries. One model, the Cambridge Bitcoin Electricity Consumption Index, begins by assessing the profitability threshold of different types of mining equipment.[9] It then develops a hypothetical range of energy use. The lower bound is the theoretical minimum total electricity use, assuming that miners use the most energy-efficient equipment available. The upper bound assumes that miners use the least efficient hardware that is still profitable. In between these bounds is the Index's "best-guess estimate." Using this number, the Index updates its estimate of Bitcoin network's daily electricity load every 24 hours. It currently estimates use of 17.49 GW, or 153.31 TWh annually.

[7] BBC, https://www.bbc.com/news/technology-56012952

[8] NASDAQ, https://www.nasdaq.com/articles/how-much-energy-does-bitcoin-really-consume-2021-05-13

[9] CBECI, https://ccaf.io/cbeci/index

Another approach, the Bitcoin Energy Consumption Index (BECI), relies on levels of crypto mining income to estimate electricity consumption. This methodology assumes that higher revenues will cause miners to spend more money on computer machinery, thus increasing energy use.[10] The BECI provides some of the highest estimates of Bitcoin energy use, at 204.50 TWh annually. But some experts reject this attempt to quantify Bitcoin's energy consumption, arguing that the calculations are based on weak assumptions, and that estimating power consumption based on miner revenue "introduce[s] multiple layers of error and uncertainty."[11]

[10] Digiconomist, https://digiconomist.net/bitcoin-electricity-consumption ; see also Cell, https://www.cell.com/joule/fulltext/S2542-4351(18)30177-6

[11] CNBC, https://www.cnbc.com/2017/12/21/no-bitcoin-is-likely-not-going-to-consume-all-the-worlds -energy-in-2020.html

There is further disagreement over the amount of energy used per Bitcoin transaction, and whether this metric is even a sensible way to measure energy consumption. First, only some portion of transactions take place "on chain," that is, require verification on the blockchain and therefore necessitate the energy-intensive PoW consensus mechanism. Many transactions occur "off chain" on crypto exchanges (such as Coinbase), where the energy consumption is orders of magnitude smaller. Second, Bitcoin's relatively high energy usage is associated with the production of blocks, not the processing of individual transactions. A block represents the permanent record of a set of the most recent transactions not yet validated by the network. Once the block is validated, the block is permanently closed and cannot be changed. At any given algorithmic difficulty, the same energy will be used to produce a block whether it contains one transaction or two thousand transactions.[12]

[12] CBECI, https://ccaf.io/cbeci/faq

An example of this disagreement is the BECI's argument that each Bitcoin transaction uses the same energy as about 59 days' worth of power used by the average American household,[13] and has a carbon footprint equal to over 2 million transactions using a Visa card.[14] Others point out that this analysis fails to account for the energy used by banking networks to complete transactions, which includes brick and mortar buildings, servers, transportation costs, customer service, dispute resolution centers, and ATM networks. Taking into account the full carbon footprint of the banking industry, rather than focusing on a single element of the transaction, illustrates why many believe that crypto is less energy intensive in comparison.[15]

[13] Coindesk, https://www.coindesk.com/business/2021/08/18/how-much-energy-does-bitcoin-use/

[14] Digiconomist, https://digiconomist.net/bitcoin-energy-consumption

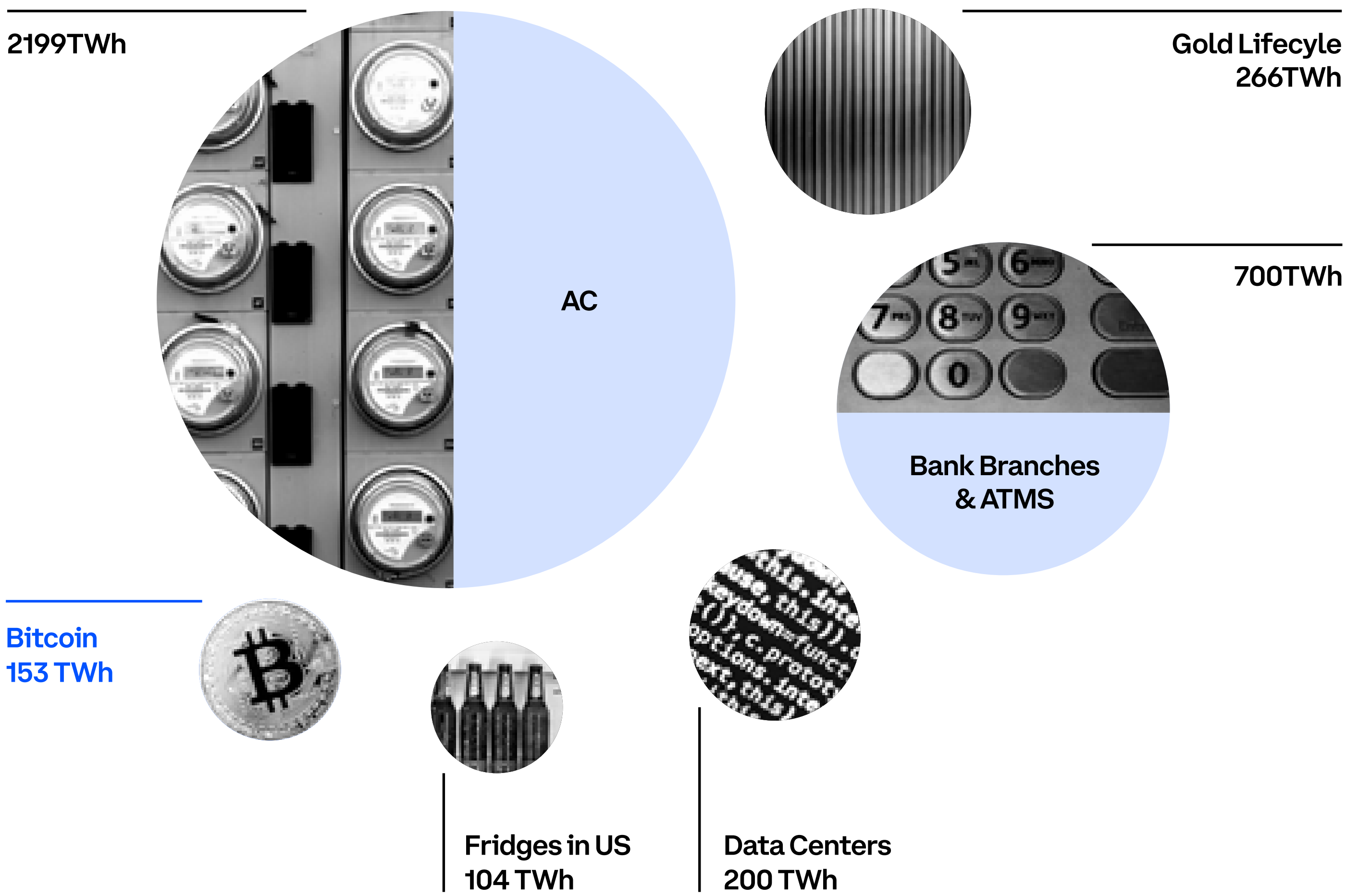
[15] HackerNoon, https://hackernoon.com/the-bitcoin-vs-visa-electricity-consumption-fallacy-8cf194987a50

While apples-to-apples comparisons may be difficult, some comparisons are illustrative: Bitcoin typically consumes less energy than gold mining each year, and substantially less than industries like iron, steel, and paper. It uses about 5% of the energy consumed by air conditioning. Bitcoin's share of the total energy consumption in the world annually is 0.31%.

[16] NASDAQ, https://www.nasdaq.com/articles/a-comparison-of-bitcoins-environmental-impact-with -that-of-gold-and-banking-2021-05-04

[17] CBECI, https://ccaf.io/cbeci/index/comparisons

Energy Amounts Used By Different Technologies (TWh)



Data from: Cambridge Bitcoin Electricity Consumption Index
https://ccaf.io/cbeci/index/comparisons
https://hassmccook.medium.com/comparing-bitcoins-environmental-impact-f56b18014f64

PART 3

Crypto's Carbon Footprint

As noted above, it is important to distinguish between electricity consumption and environmental impact. What ultimately impacts the climate is not crypto's electricity consumption, but the carbon footprint of the energy sources used to produce that electricity. Increased consumption of coal-generated electricity, for example, will have a much worse environmental impact than energy generated by renewable sources such as wind and solar.

Measuring Crypto's Use of Sustainable Energy Sources

Crypto mining lends itself well to renewables use. Unlike most industries, mining can happen far from its end use, has a steady demand, and can be interrupted at any time of day. Because mining equipment is relatively mobile, miners can set up new facilities fairly quickly. This allows them to take advantage of energy sources that vary by season and location, such as hydropower and wind power. But these same variations also lead to "wildly different estimates" of renewables use.[18] Analyses of Bitcoin's renewables use range from about 40% to almost 75%.[19] It is worth noting that other industries have a much more difficult time transitioning to renewable energy use: in the United States, transportation's renewable energy use is 5% and commercial energy use is 3%.[20]

As with the question of energy use overall, this uncertainty is due in part to the decentralized, anonymous nature of miners. Most data in this area relies on surveys of mining facilities. In 2021, the Bitcoin Mining Council, an industry group, collected information from about 32% of the global Bitcoin network. Based on the results, it estimated that the mining industry used about 56% sustainable energy during Q2 2021.[21] This percentage would make it one of the most sustainable industries worldwide. Another survey of over 100 miners in 2020, combined with a map of the geographic distribution of Bitcoin hashpower, concluded that only about 29% of Bitcoin mining was powered by sustainable energy.[22] Specifically, miners were relying heavily on hydroelectric power, coal, and natural gas, and to a lesser extent utilizing oil, nuclear power, and renewables such as wind, solar, and geothermal energy.

These distinctions lead to varying estimates of crypto's carbon footprint. For example, a 2017 study found that crypto mining in China had a carbon intensity of 711, while Sweden's was just 13, and Iceland's was zero, thanks to the country's cold climate and abundant geothermal energy.[23] This means that although Bitcoin's energy use might be comparable to that of a small country, its carbon footprint could be much smaller. Studies have estimated Bitcoin's annual carbon footprint to be between 57 and 97 million tons.[24] Returning to the imperfect comparison that people make between Bitcoin and countries, Thailand's carbon footprint is estimated to be 258 million tons[25] and Malaysia is estimated to be 273 million tons.[26] Making a comparison to refrigerators is further complicated by the GHG emissions that refrigerants leak, significantly increasing refrigerators' carbon footprint beyond their energy use.

[18] New York Times (Sept. 3, 2021), https://www.nytimes.com/interactive/2021/09/03/climate/bitcoin-carbon-footprint-electricity.html

[19] Id.

[20] U.S. Energy Information Agency, https://www.eia.gov/energyexplained/us-energy-facts/

[21] Bitcoin Mining Council, https://bitcoinminingcouncil.com/wp-content/uploads/2021/07/2021.07.01-Mining-Council-Press-Release-Q2.pdf

[22] Cambridge Centre for Alternative Assets, https://www.jbs.cam.ac.uk/wp-content/uploads/2021/01/2021-ccaf-3rd-global-cryptoasset-benchmarking-study.pdf

[23] Digiconomist, https://digiconomist.net/bitcoin-energy-consumption/ (The number reflects the grams of carbon dioxide equivalent per kilowatt-hour of electricity generated (gCO2eq/kWh))

[24] Forex Suggest, https://forexsuggest.com/global-impact-of-crypto-trading/ ; Bitcoin Energy Consumption Index - Digiconomist

[25] Our World in Data, https://ourworldindata.org/co2/country/thailand

[26] Our World in Data, https://ourworldindata.org/co2/country/malaysia

It is also important to note that different segments of the crypto industry have vastly different carbon footprints. While mining gets the most attention, other segments of the industry such as crypto exchanges and custody use much less energy. More data is still needed to accurately assess the impact of the crypto industry as a whole, but it is clear that simply measuring electricity use by mining presents an incomplete picture of crypto's climate impact.

Use of Renewable Energy Sources

Many reports about crypto's use of non-renewable energy sources suggest a very climate-dirty industry, but these reports fail to account for crypto's design and recent developments. The mobility and interruptibility of crypto mining incentivizes miners to seek out the most cost-efficient energy sources even more than other industries.

By design, crypto mining is a better fit for variable renewable energies like solar and wind, because mining can be interrupted without incurring large ramp up and shut down costs. Furthermore, renewable electricity costs have fallen sharply over the past ten years due to better technology, economies of scale, and supply chain competition. Specifically, solar power costs declined by 82%, and onshore wind costs declined by 39%.[27] When measuring the "levelized cost of energy," which includes the total cost of building and operating a facility over its lifetime, renewable energy increasingly costs much less than fossil fuels, and will continue to cost less over time.[28]

Crypto mining's mobility means that it can be co-located near the location of the energy source, and does not require expensive transmission lines and power grids. For example, governments and businesses are capitalizing on these cheaper, cleaner energy sources. El Salvador, which declared Bitcoin a national currency in 2021, is building wells to harness geothermal energy for mining.[29] Iceland has experienced a so-called "new gold rush" over the past decade, with miners taking advantage of the country's abundant geothermal energy.[30] In the United States, Square, Inc., is investing $5 million to build a solar-powered Bitcoin mining facility, aiming to provide a proof of concept for a 100% renewable-energy Bitcoin mine at scale.[31] Mining company Digihost has built mining facilities in New York that rely partly on power from hydro generation around Niagara Falls.

[27] International Renewable Energy Agency, https://www.irena.org/publications/2020/ Jun/Renewable-Power-Costs-in-2019

[28] Forbes, https://www.forbes.com/sites/energyinnovation/2020/01/21/renewable-energy-prices- hit-record-lows-how-can-utilities-benefit-from-unstoppable-solar-and-wind/?sh=44f20c1e2c84

[29] Bitcoin.com, https://news.bitcoin.com/el-salvador-to-add-more-geothermal-energy-sources-to-power- bitcoin-city/

[30] Think Geoenergy, https://www.thinkgeoenergy.com/bitcoin-mining-fuelled-by-geothermal-power- in-iceland-to-create-new-gold-rush/

[31] Bloomberg, https://www.bloomberg.com/news/articles/2021-06-05/square-to-invest-5m-in-solar- powered-bitcoin-mining-facility

Finally, miners are making use of flared gas, a byproduct of oil drilling. When oil companies drill for gas and hit patches of natural gas but lack the infrastructure and pipeline to capture the gas, the company must burn the gas. This process is known as flaring and it releases harmful carbon emissions, although less than allowing the gas to be released directly into the atmosphere.

Bitcoin mining has reduced CO2-equivalent emissions from gas flaring by up to 63%.[32]

In April 2021, a group of crypto entities launched the Crypto Climate Accord, aiming to power 100% of the world's blockchain with renewable energy by 2025. [33] The Accord also promotes the use of energy tracking tools, or "green hashtags," and the development of digital #ProofOfGreen solutions. This move toward renewables is likely to be supported by consumers, who have a stated interest in supporting sustainable businesses and seeking out energy-efficient brands.

Transitioning to Proof of Stake, and the Rise of "Green" Coins

In addition to crypto's design features that already make it more economically aligned to use renewable energy than any traditional industry sector, the crypto industry is continuing to innovate by developing alternative consensus mechanisms that require even less energy consumption.

Proof of Stake (PoS) is an alternative consensus mechanism that uses much less energy than PoW. PoS can be thought of as virtual mining. Owners of a cryptocurrency can "stake" their coins in an escrow account to show their availability to mine that particular crypto. Rather than having participants try to solve energy-intensive cryptographic puzzles, the network randomly selects a participant based on the amount staked. This party adds a new block to the chain.

Because PoS does not require miners to solve cryptographic puzzles, it is considerably less energy-intensive.[34] Transitioning from a PoW to PoS mechanism could lead to dramatically less energy consumption – up to 1/10,000th of the current requirement.[35] Notably, the world's second most popular cryptocurrency, Ethereum, plans to switch from PoW to PoS in 2022. This transition to "Ethereum 2.0" is expected to spur a 99% decline in Ethereum's energy use.[36] Although some analysts have speculated that Bitcoin could someday transition to PoS, most see this as unlikely because of the difficulty in coordinating technical efforts and the importance of PoW to Bitcoin's value.[37]

[32] Business Insider, https://markets.businessinsider.com/currencies/news/bitcoin-mining-flare-gas- btc-energy-crusoe-energy-coinbase-winklevoss-2021-6-1030537177 (Coinbase is an investor)

[33] Crypto Climate Accord, https://cryptoclimate.org/

[34] Coinbase Blog, https://www.coinbase.com/learn/crypto-basics/what-is-proof-of-work-or-proof-of-stake

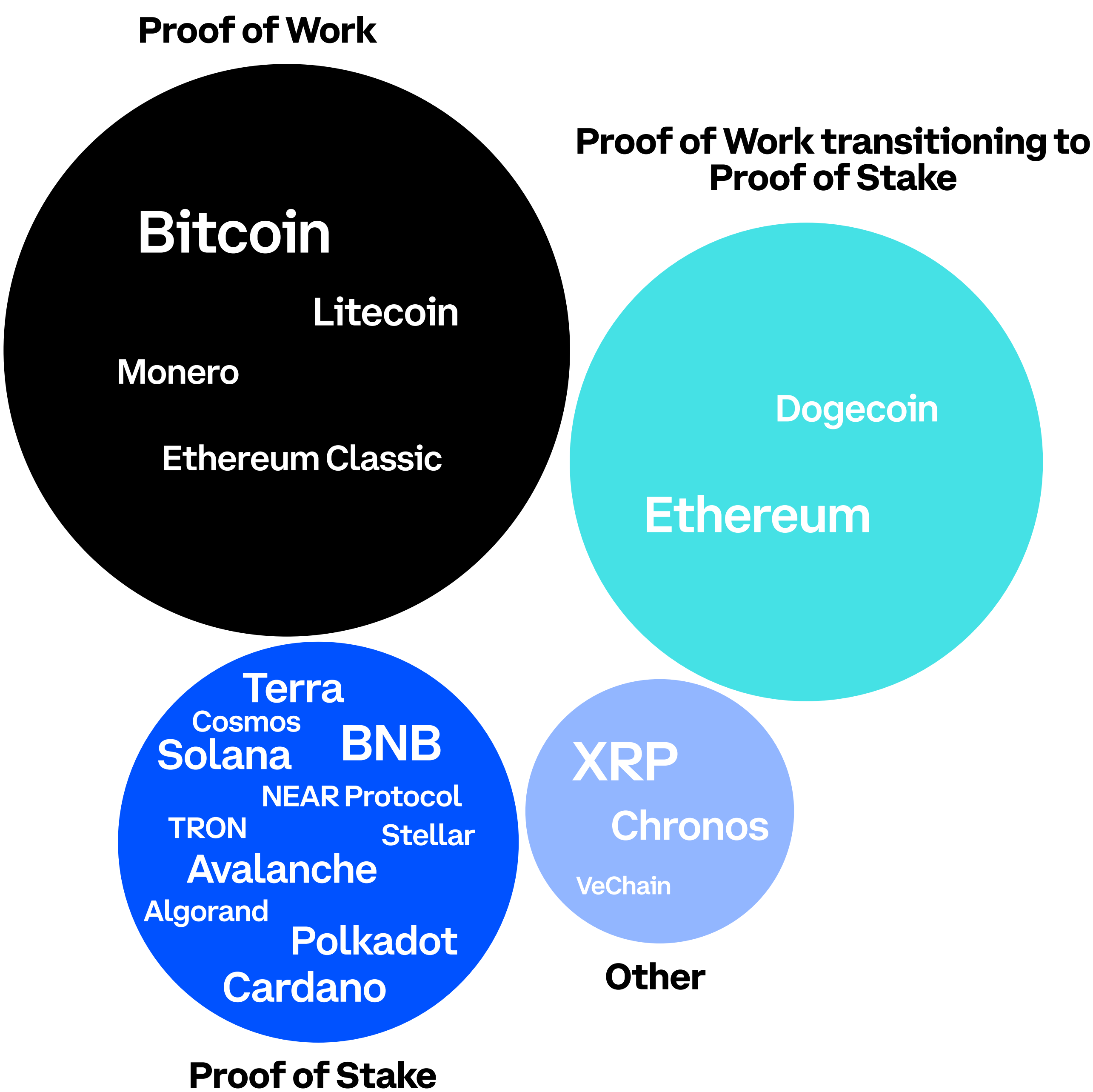
[35] Business Insider, https://www.businessinsider.in/cryptocurrency/news/heres-how-ethereum-2-0-cryptocurrency-promises-to-be-green-scalable-and-far-more-efficient/articleshow/83003150.cms

[36] Id.

[37] Cointelegraph, https://cointelegraph.com/news/bitcoin-will-follow-ethereum-and-move-to-proof-of- stake-says-bitcoin-suisse-founder ; Solberg Invest, https://solberginvest.com/blog/will-bitcoin-be-proof -of-stake-in-the-future/

The figure below shows the list of the top 20 layer 1 cryptocurrencies, and whether they are using a Pow or a PoS consensus mechanism. The large majority of layer 1 cryptocurrencies use PoS, however, in terms of market size (the size of the circle), PoW is still dominant.

Consensus Mechanisms for Top 20 Layer 1 Cryptocurrencies



Although almost all cryptocurrencies launched in the past several years have relied on PoS, it is not obvious that PoS mechanisms are superior to PoW – each has tradeoffs.

On the one hand, PoS is less energy-intensive than PoW and, under certain conditions, could be more secure against 51% attacks.[38] However, it relies on economic incentives to ensure that the network is secure, final, and operating continuously. Issues about chain liveliness (e.g. 33% attacks) and, finality (e.g. long range attacks) are usually addressed using economic incentives (e.g. slashing) in PoS, while in PoW they are not an issue because the consensus operates through the decentralized, cryptographic puzzle-solving, rather than staking.

Finally, other cryptocurrencies have embraced different consensus mechanisms that are also more energy-efficient. Ripple (XRP) uses its own Ledger Consensus Protocol to validate account balances and transactions. It claims that this approach is 57,000 times more energy efficient than Bitcoin.[39] Chia, introduced in a Green Paper in 2019, uses a "proof of space and time" algorithm that requires validators to reserve storage for a certain amount of time to earn crypto.[40] And other so-called "green" coins relate directly to eco-friendly interests.[41] For example, homeowners with solar panels typically receive certificates from their energy company in exchange for feeding electricity back into the grid. SolarCoin lets users trade these certificates for tokens. As the tokens rise in price, SolarCoin hopes to incentivize solar energy use. And Powerledger is a token that aims to facilitate peer-to-peer trading of energy and environmental commodities.

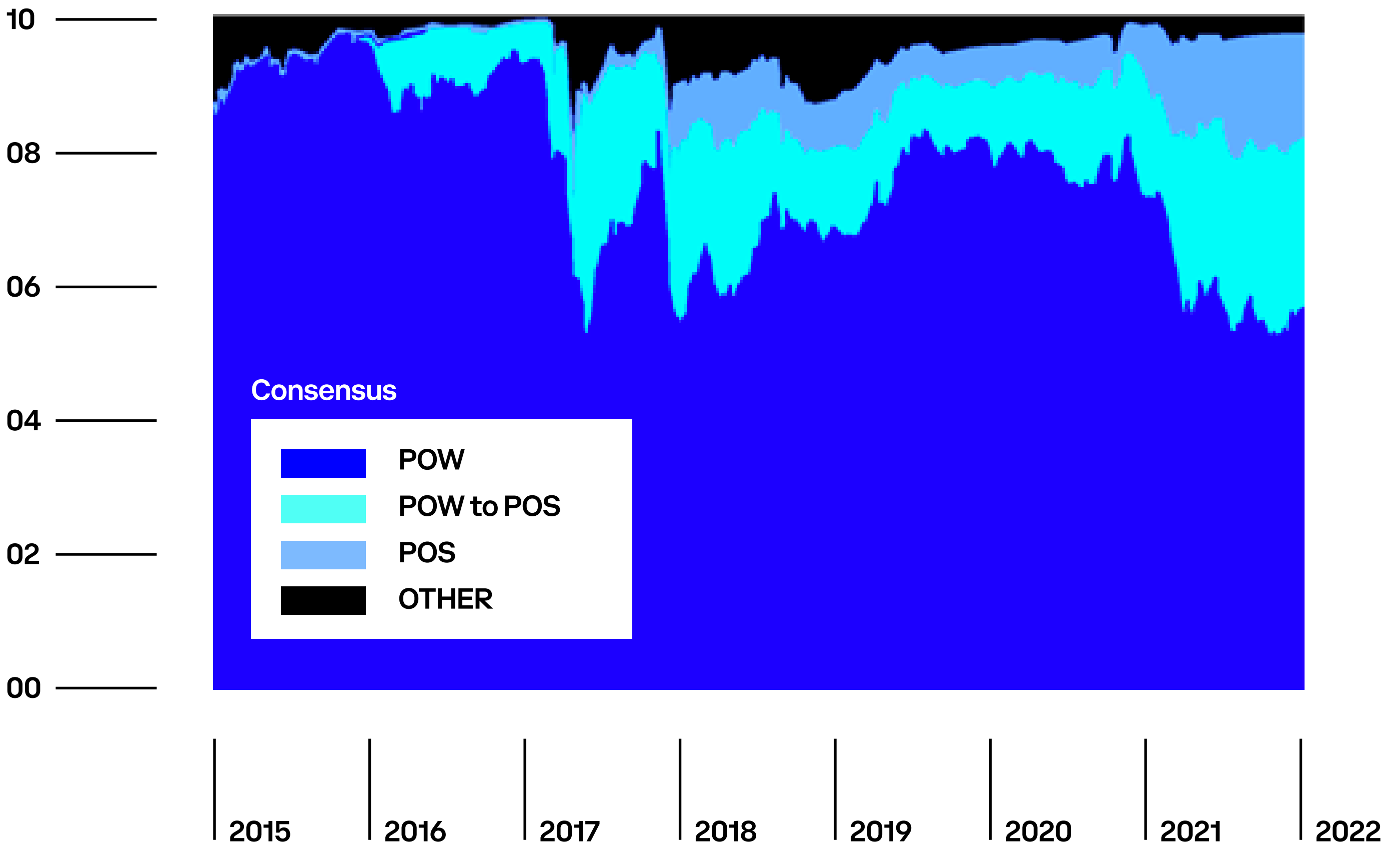
[38] Financial Times, https://www.ft.com/content/c536c040-3a87-4fb8-a9e5-a446c8ff9d3d

[39] Ripple, https://ripple.com/insights/the-environmental-impact-cryptocurrency-mining-vs-consensus/

[40] Chia, https://www.chia.net/greenpaper/

[41] NBC News, https://www.nbcnews.com/tech/tech-news/cryptocurrency-goes-green-proof-stake-offer -solution-energy-concerns-rcna1030

Share of Market Adoption By Consensus Mechanism



Using market capitalization data from 33 of the most popular network cryptocurrencies, this graphic shows the relative market capitalization of cryptocurrencies relying on proof of work, proof of stake, and other consensus mechanisms (such as Proof of Authority) from 2015 to the present.[42] As demonstrated by the graphic, the market adoption of PoS-based cryptocurrencies has seen steady growth as compared to cryptocurrencies backed by PoW in recent years. This growth is even more significant when considering that high market-cap coins like Ethereum and Dogecoin are currently transitioning their protocols from PoW to PoS. Notwithstanding the historical shift towards more energy-efficient consensus mechanisms, it is unclear whether such a trend will continue in the future. For the most part, it will depend on two main factors: (i) the successful transition of Ethereum from PoW to PoS, and the relative success of PoS cryptocurrencies relative to Bitcoin.

[42] This graphic includes only those cryptocurrencies that rely on "layer 1" protocols, which refers to the base blockchain architecture onto which third party networks (layer 2) and decentralized applications (layer 3) can integrate. Any layer 2 or layer 3 integration will necessarily adopt the consensus mechanism used by the layer 1 base.

CONCLUSION

Looking Ahead

The impact of cryptocurrencies on the climate presents serious, novel questions that will take time and further research to answer. The reality is that the innovations of this industry have outstripped the research necessary to assess their impact. But the research is critical for all of us to have a shared understanding of crypto's future. U.N. experts have already noted that "cryptocurrencies and the technology that powers them (blockchain) can play an important role in sustainable development, and actually improv[e] our stewardship of the environment."[42] While we still lack an agreed-upon methodology for measuring crypto's climate impact, three areas in particular are ripe for further research:

- The overall carbon footprint of the crypto industry. The sources of energy used to power mining and validating is not yet consistently traced, leading to widely disparate estimates of crypto's actual carbon footprint.
- The net climate impact of crypto's disruption of traditional financial sectors. Providing the right apples-to-apples comparison of crypto's climate impact is not yet readily available. The net impact of crypto's potentially disruptive disintermediation of traditional financial sectors, and the impact of greater financial access to new populations, has yet to be well-quantified or measured.
- The tradeoffs among different consensus mechanisms. Innovation in the underlying consensus mechanisms has dramatically improved energy efficiency. From Bitcoin's first appearance a little over a decade ago to the development and adoption of new cryptocurrencies and protocols in just the last few years, the energy efficiency of cryptocurrency has improved at a rate not seen by legacy industries. While we have abstract understandings for how these improvements affect energy efficiency, we have insufficient data to compare the tradeoffs among different consensus mechanisms; for example, weighing the efficiency gains against variation in reliability and scalability.

[43] UN News, https://news.un.org/en/story/2021/06/1094362